Atomic physics in dense plasmas

F.B. Rosmej[1,2], D. Riley[3], R.W. Lee[4], A Tauschwitz[5] et al..

[1]Université de Pierre et Marie Curie, Paris, France
[2]LULI, Palaiseau, France
[3]Queens University of Belfast, UK
[4]LLNL, USA
[5]GSI Darmstadt, Germany

frank.rosmej@upmc.fr

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Contents

I. Introduction

Atomic physics I.

- **Isolated atoms and ions**

  - Atomic structure: Wavefunctions
    Energy levels

  - Transitions: Wavelengths
    Radiative decay rates A
    Autoionising rates Γ

Well known, in particular for highly charged ions

Theory/simulations: predictive

Atomic physics II.

- **Low density plasmas**

  - Collisions: Excitation
    Ionisation
    Radiative recombination
    Dielectronic recombination

  - Atomic kinetics:

$$\frac{dn_j}{dt} = -n_j \sum_k depop_{jk} + \sum_l n_l \; pop_{lj}$$

  - Radiation emission:

$$I(\omega) = \sum_{j,i} \hbar\omega_{ji} \; n_j \; A_{ji} \; \varphi_{ji}(\omega)$$

Today: theory is very predictive, excellent diagnostics

Atomic physics III.

- **High density plasmas**

  - Collisions: Excitation/De-exciation
Ionisation/3-body recombination
Radiative recombination
Dielectronic recombination

  - Photon transport: Radiative decay
Stimulated emission/absorption

  - Atomic kinetics: $$\frac{dn_j}{dt} = -n_j \sum_k depop_{jk} + \sum_l n_l \; pop_{lj}$$

  - Radiation emission: $$I(\omega) \approx \sum_{j,i} \hbar\omega_{ji} \; n_j \; A_{ji} \; \Lambda_{ji} \; \varphi_{ji}(\omega)$$

Today: theory is rather predictive, unique diagnostics

What is a dense plasma ?

Collisions are equally/more important as radiative decay rates:

$$n_e \; C \;\approx\; A$$

$$C \;\propto \frac{1}{Z^3} \qquad A \;\propto Z^4 \qquad n_e \;\frac{1}{Z^7} \;\approx\; const$$

$$\eta_e \;=\; \frac{n_e}{Z^7}$$

For hydrogen:

$n_e \approx 10^{18} \; cm^{-3}$ Boltzmann population statistics: LTE

For Molybdene: $n_e \approx 10^{29} \; cm^{-3}$

What is a hot plasma ?

Thermal energies have to be compared with atomic energies:

$$E_{thermal} \approx E_{Atom}$$

$$E_{thermal} \propto kT_e \quad E_{Atom} \propto Z^2 Ry \qquad \frac{Z^2 Ry}{kT_e} \approx const$$

$$\beta_e = \frac{Z^2 Ry}{kT_e}$$

For hydrogen: $kT_e \approx 10 \ eV$

For Molybdene: $kT_e \approx 18 \ keV$

What is a coupled plasma ?

Coulomb energies between particles
have to be compared with thermal ones:

$$E_{Coulomb} \approx E_{thermal}$$

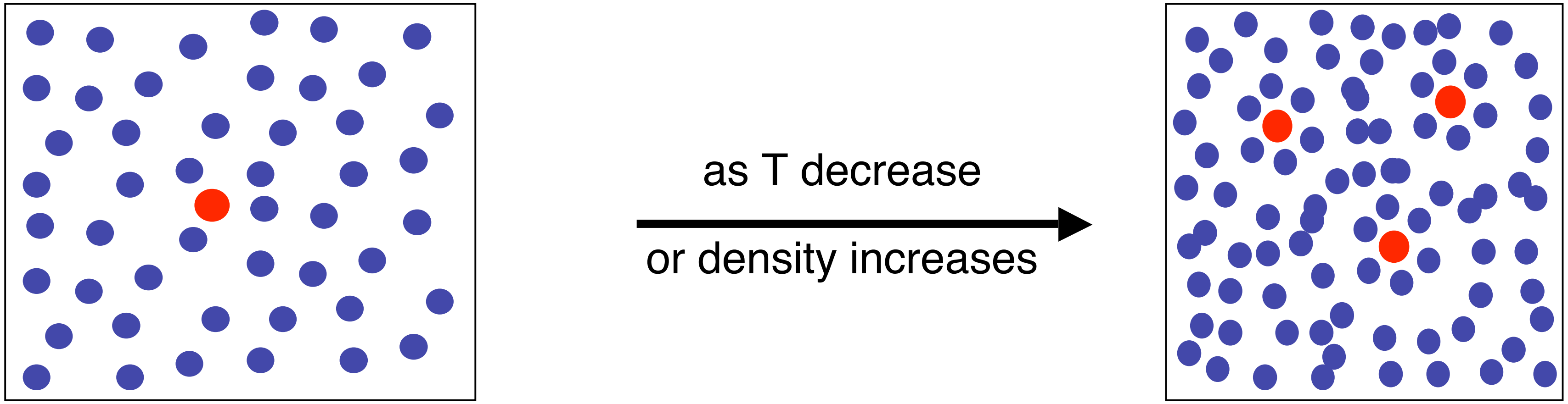
$$E_{Coulomb} \propto Z_i^2 n_i^{1/3} \qquad E_{thermal} \propto kT_i \qquad \frac{Z_i^2 n_i^{1/3}}{T_i} \approx const$$

$$\Gamma_{ii} = 2.32 \cdot 10^{-7} \frac{Z_i^{1/3} \; n_i^{1/3}\left(cm^{-3}\right)}{kT_i\left(eV\right)}$$

Aluminum: Z = 13, $n_i = 10^{22}$ cm^{-3}, kT_i = 80 eV

$$\Gamma_{ii} \approx 10$$

The defining concept is coupling



Electric Microfield → Stark effect → Line broadening

Level depression

•
•
•

Particle statistics

Particle correlations

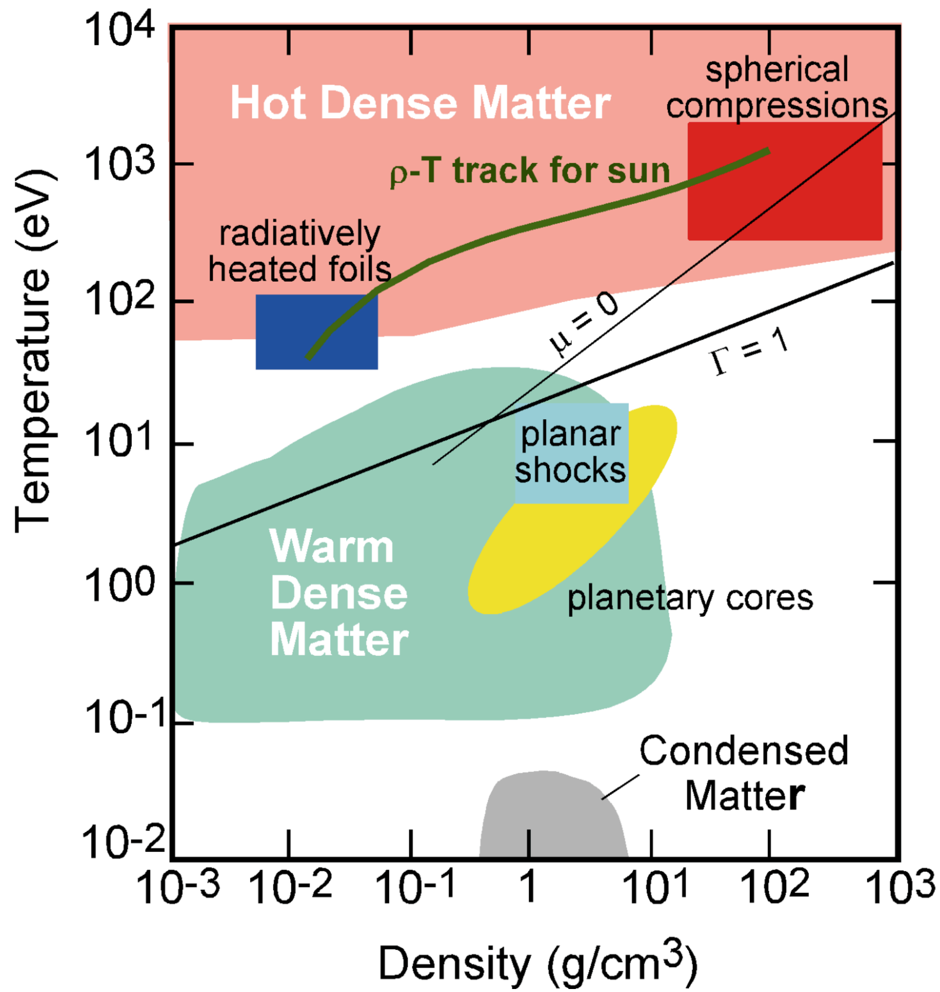
$$Z = \sum_{i=1}^{N} g_i \, e^{-E_i/kT}$$

$N = ?$

$g_i = ?$

Warm Dense Matter : The importance of finite-temperature dense matter derives from its wide occurrence

- Hot Dense Matter occurs in:
  - Supernova, stellar interiors, accretion disks
  - Plasma devices: laser produced plasmas, Z- pinches
  - Directly driven inertial fusion plasma
- WDM occurs in:
  - Cores of large planets
  - Systems that start solid and end as a plasma
  - X-ray driven inertial fusion implosion



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Atomic physics and derived quantities

Atomic Structure

Particle statistics

Atomic kinetics

Atomic physics in dense plasmas

Atoms/Ions/Molecules

Distribution of different ionisation stages

Distribution of ground and excited states

Emission

Scattering

Absorption

Transmission

Conductivity

Compressibility

Phase transitions

•
•
•

Equation of state

II. Extreme Conditions

Extreme parameter conditions

High density: $\eta_e = \frac{n_e}{Z^7}$ Large coupling: $\Gamma \propto \frac{n^{1/3}}{T}$

• To observe x-ray emission: must minimise absorption near solid density

(That is, need to have radiation exit the volume for diagnostics)

Production of x-ray emission in highly charged ions requires

$$kT_e \approx const.\ Ry\, Z^2 \approx keV$$

This means, interesting transitions can be studied only at high kT_e !

• Interesting temperature too low to thermally excite x-ray emission

Also the inconvenience
is extreme ! ☹

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Interesting experiments

What is an interesting experiment ?

An interesting experiment is an experiment which produces samples at extreme parameter conditions

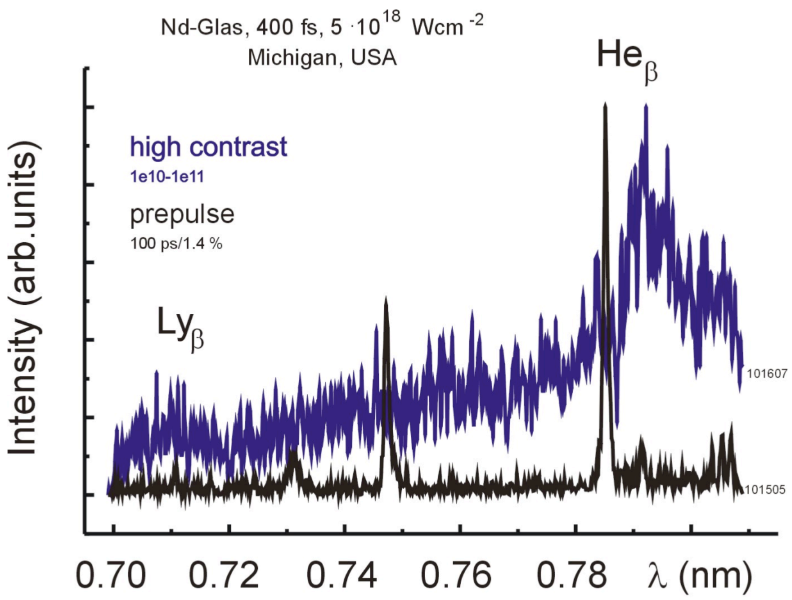
….in a manner that these samples can be well diagnosed !

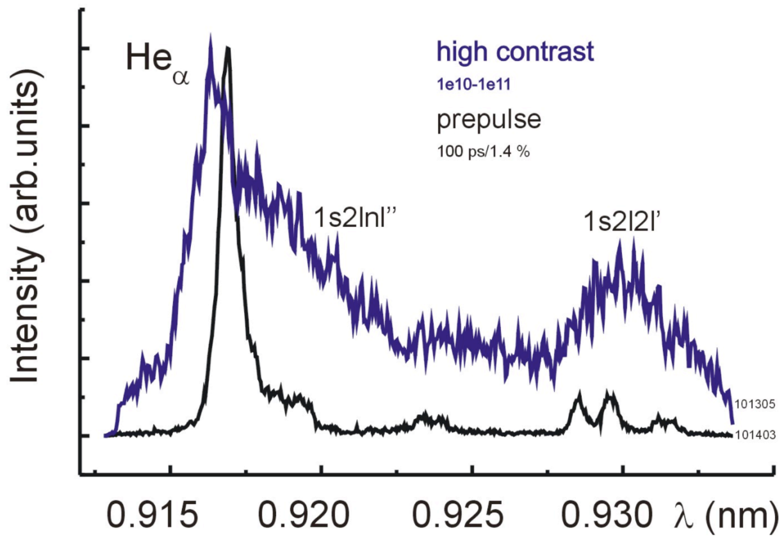
How ?

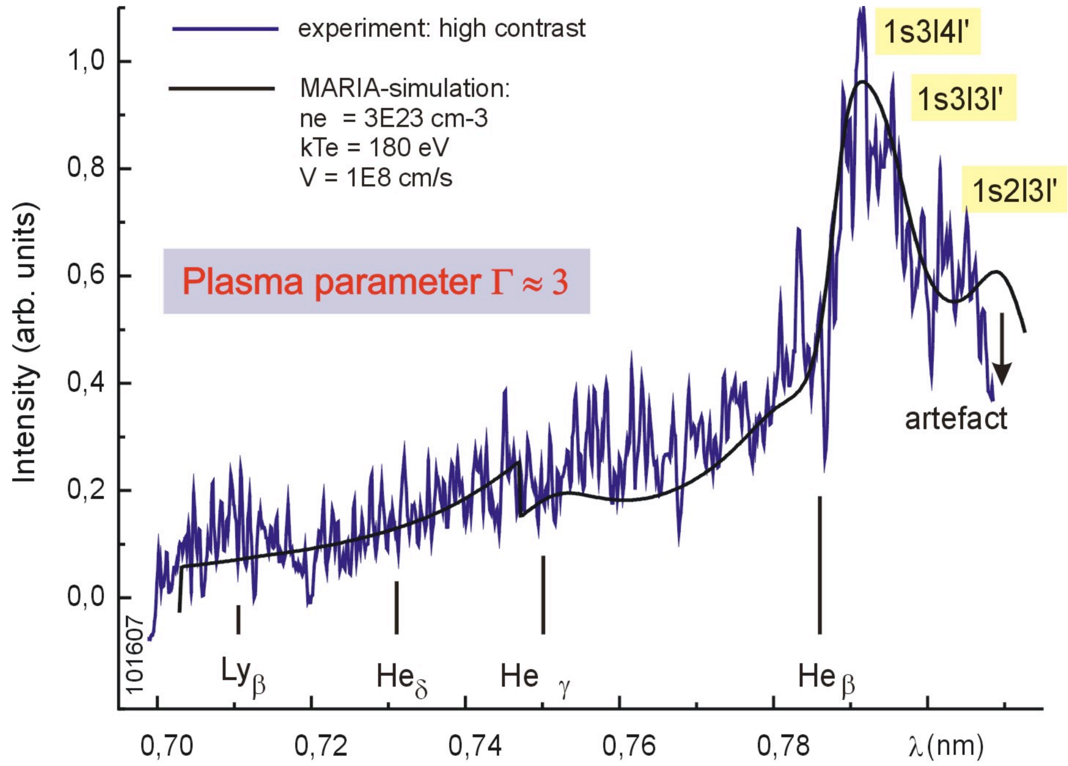
III. Optical lasers

Line/continuum shifts, level depression, line broadening

Example: dense laser produced plasma experiments





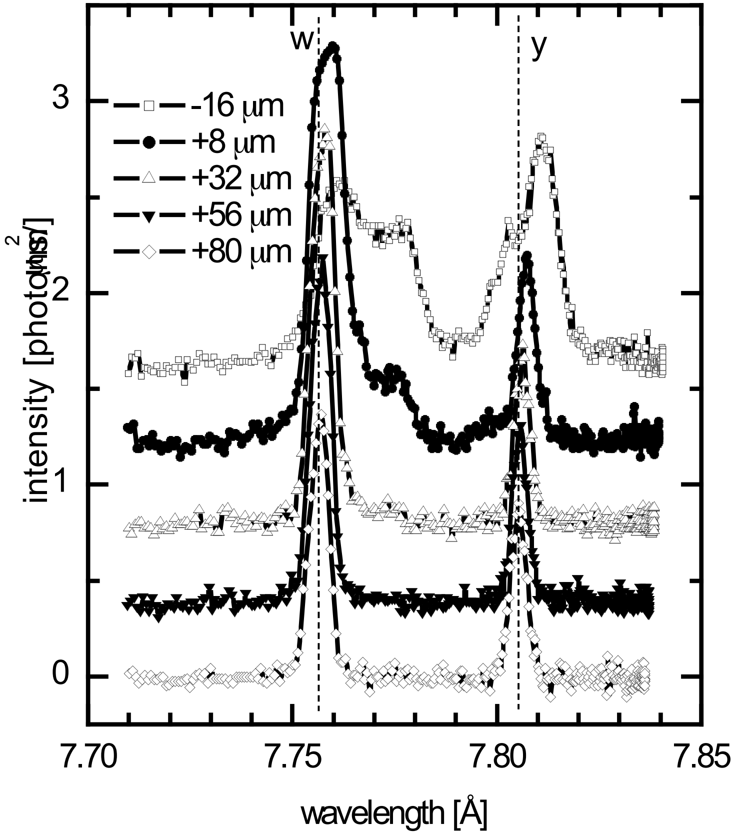


F.B. Rosmej et al., JQSRT **65**, 477 (2000)

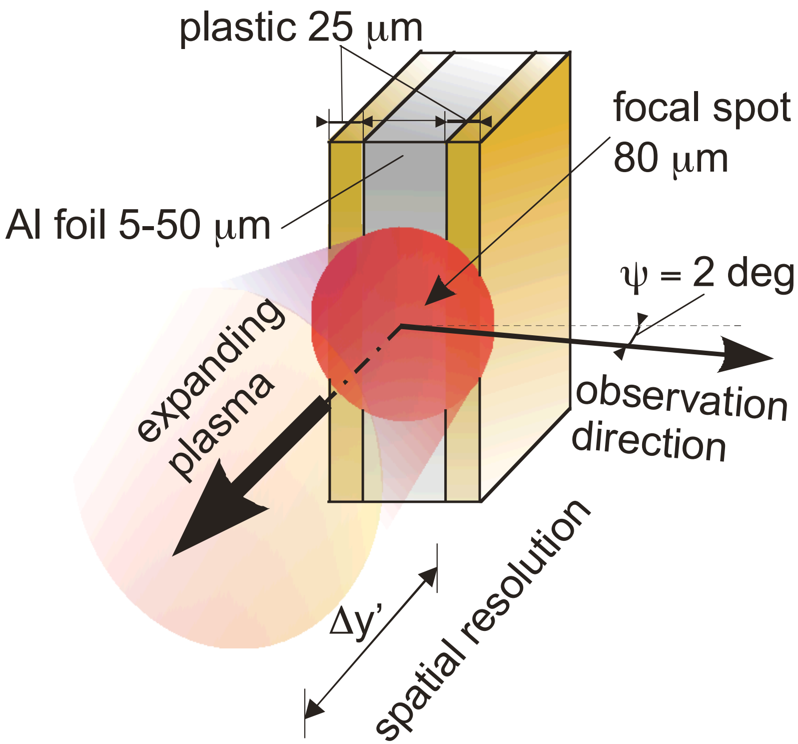
LULI: e-e exchange energy shift in dense plasmas I.

There exist one pair of suitable transitions in He-like ions:

Resonance line:	$1s^2\ ^1S_0 - 1s2p\ ^1P_1$	**"A spin in a dense plasma"**
Intercombination line:	$1s^2\ ^1S_0 - 1s2p\ ^3P_1$	



Renner et al., JQSRT **99**, 523 (2006)



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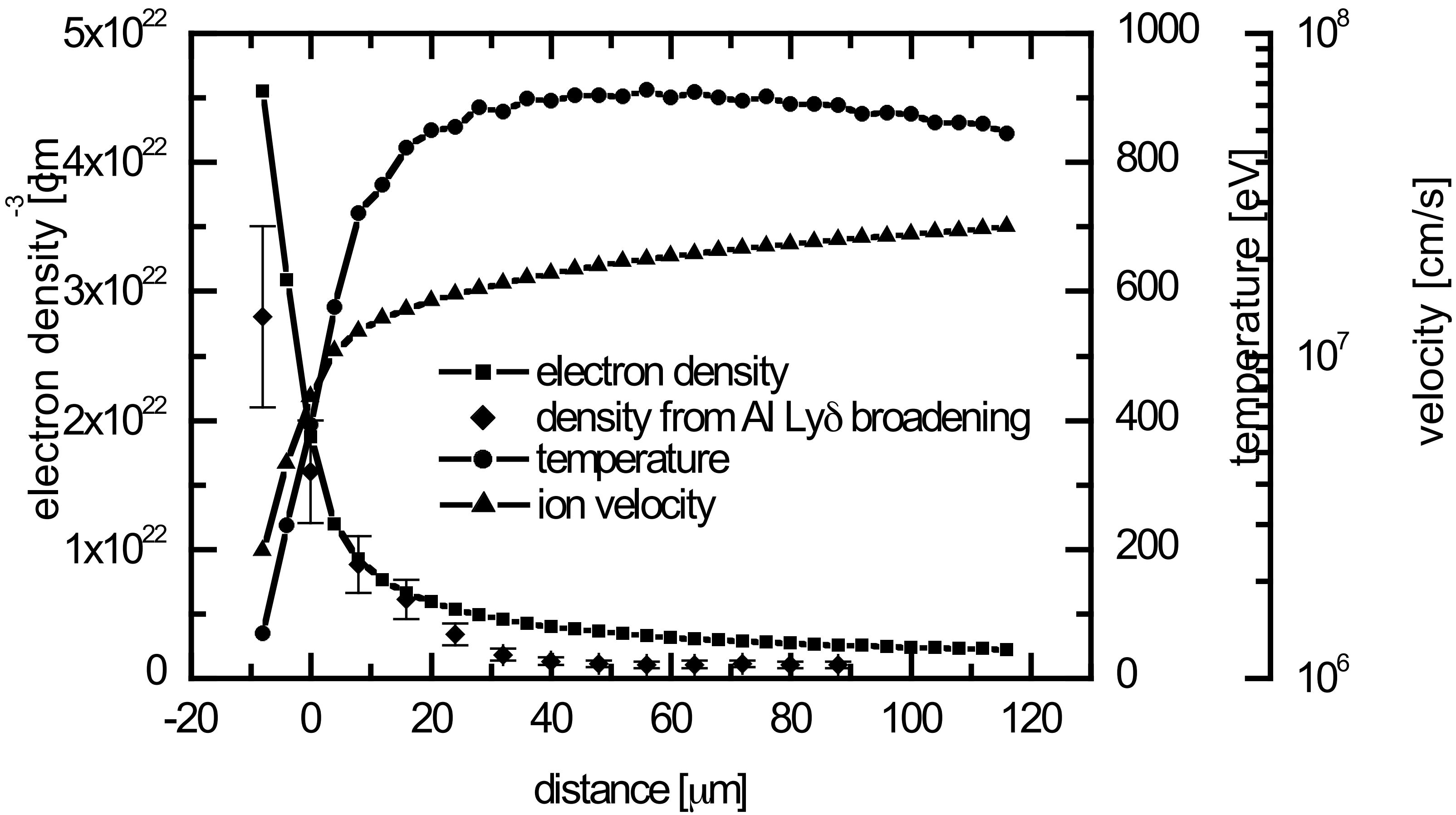
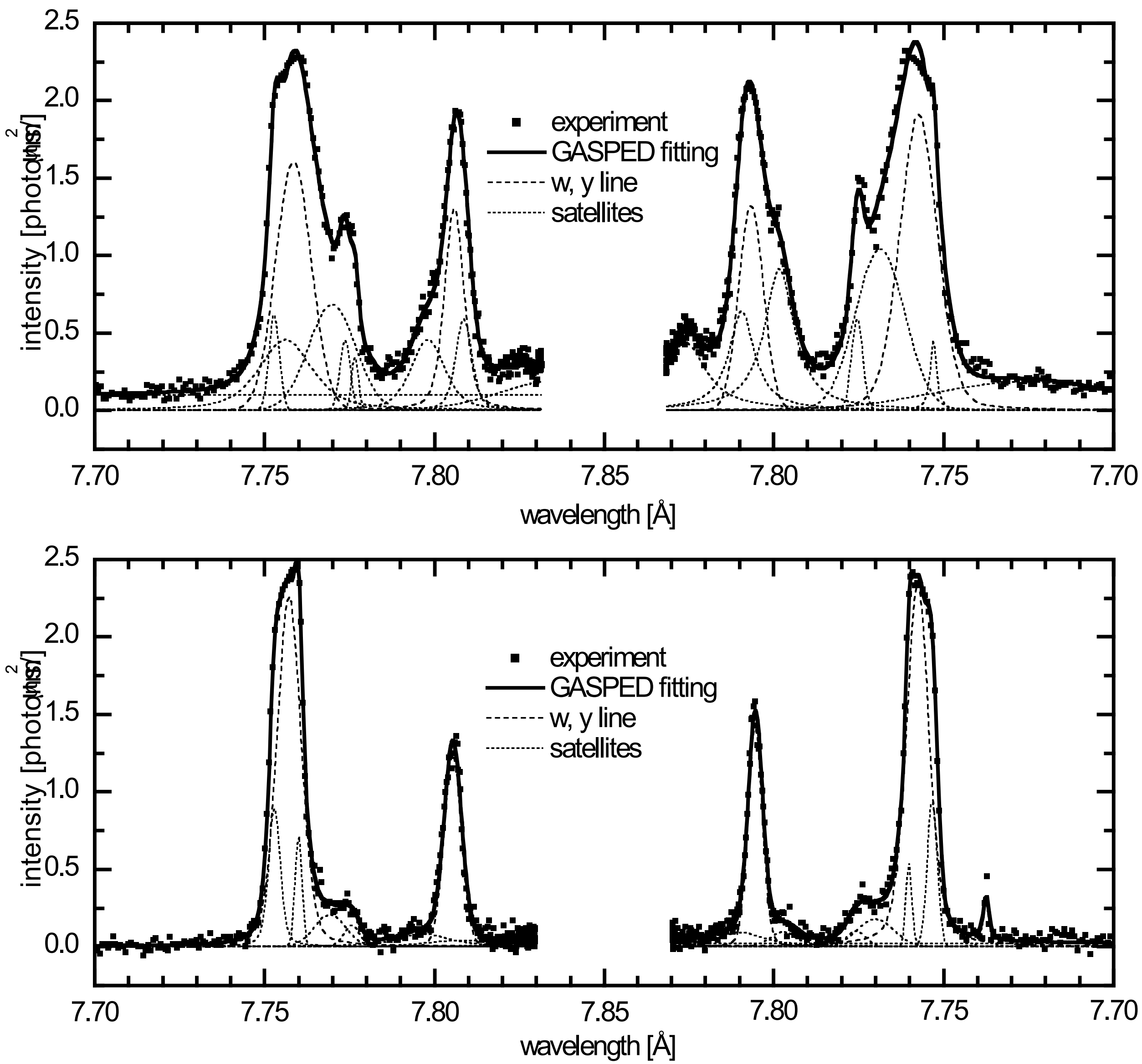
Spatial parameter variation



Renner et al., JQSRT **99**, 523 (2006)

Dielectronic satellites



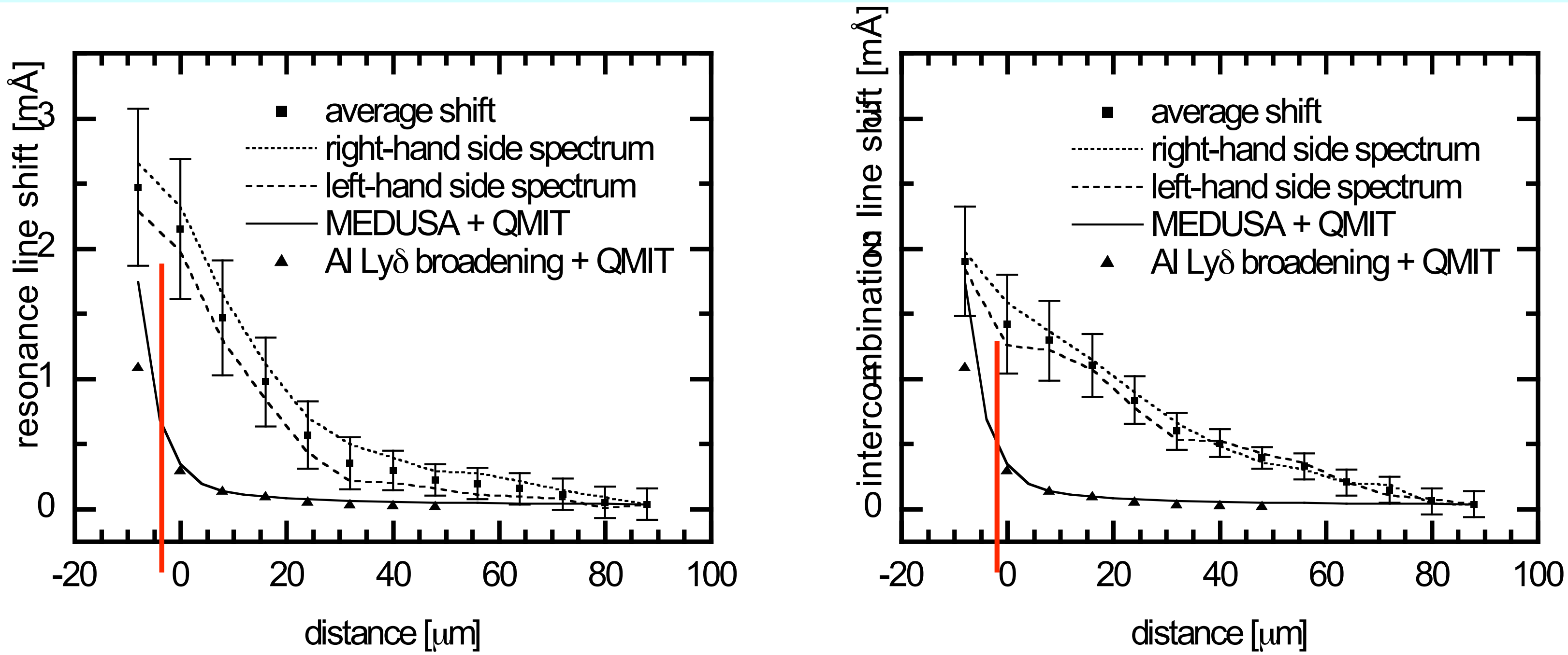
For interesting parameter regimes

Dielectronic satellites

Renner et al., JQSRT **99**, 523 (2006)

F.B. Rosmej/LULI-PAPD

e-e exchange energy shift in dense plasmas II.



Renner et al., JQSRT **99**, 523 (2006)

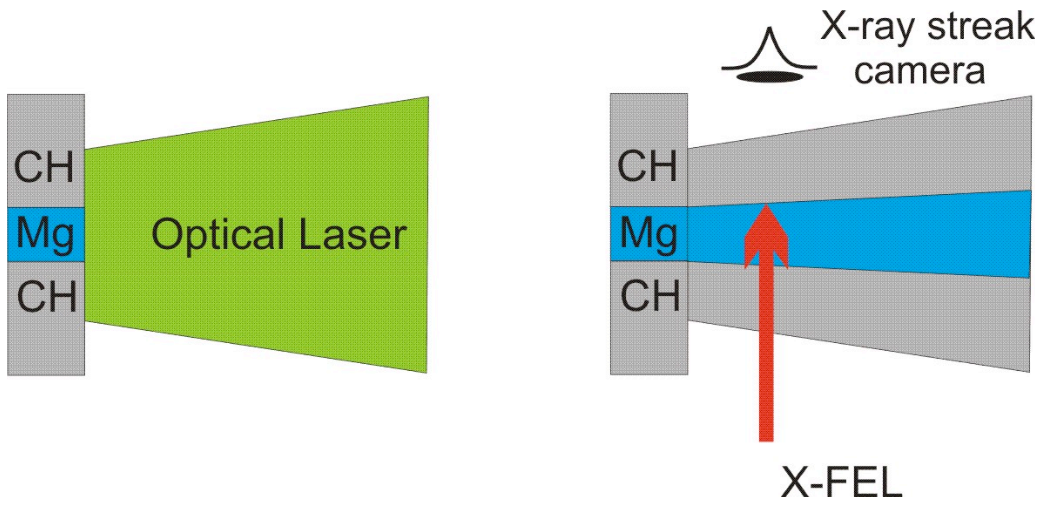
The exchange energy shift is a fundamental observation of of atomic physics in dense plasmas

Simulations of atomic physics has begun (only qualitative agreement):

X. Li, Z. Xu, F.B. Rosmej, J. Phys. B : At. Mol. Opt. Phys. **39**, 3373 (2006)

IV. X-ray lasers

Pump probe experiments



To move populations: X-ray pump rate > spontaneous decay rates A, Γ

$$Photon\ \ pump\ rate\ > A_0\, Z^4,\, \Gamma \approx 10^{12} - 10^{15}\, s^{-1},\; A_0 \approx 6\cdot 10^8\, s^{-1}$$

The planned free-electron X-ray lasers X-FEL and LCLS will allow

efficient pump rates to move even populations of HCI

→ Access to lower temperatures (higher Γ_{ii}) via photoionization.

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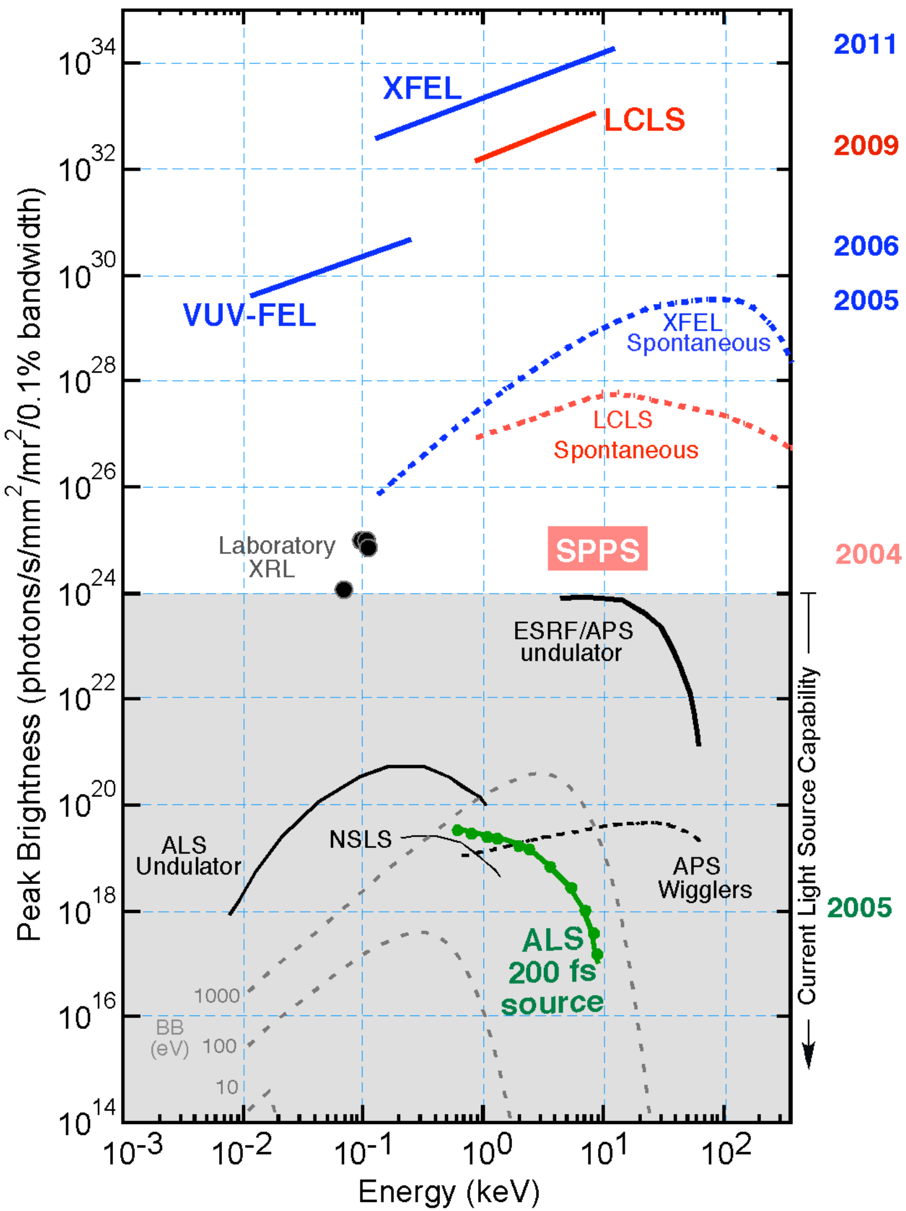
Challenges with the X-FEL: pumping

No other source,
e.g., x-ray laser
can attain the requested
parameters !

Also energy limitation:
$\lambda \sim 100$ Å

Only the X-FEL parameters enable to realize pumping of highly charged ions in dense plasmas to perform this new research.



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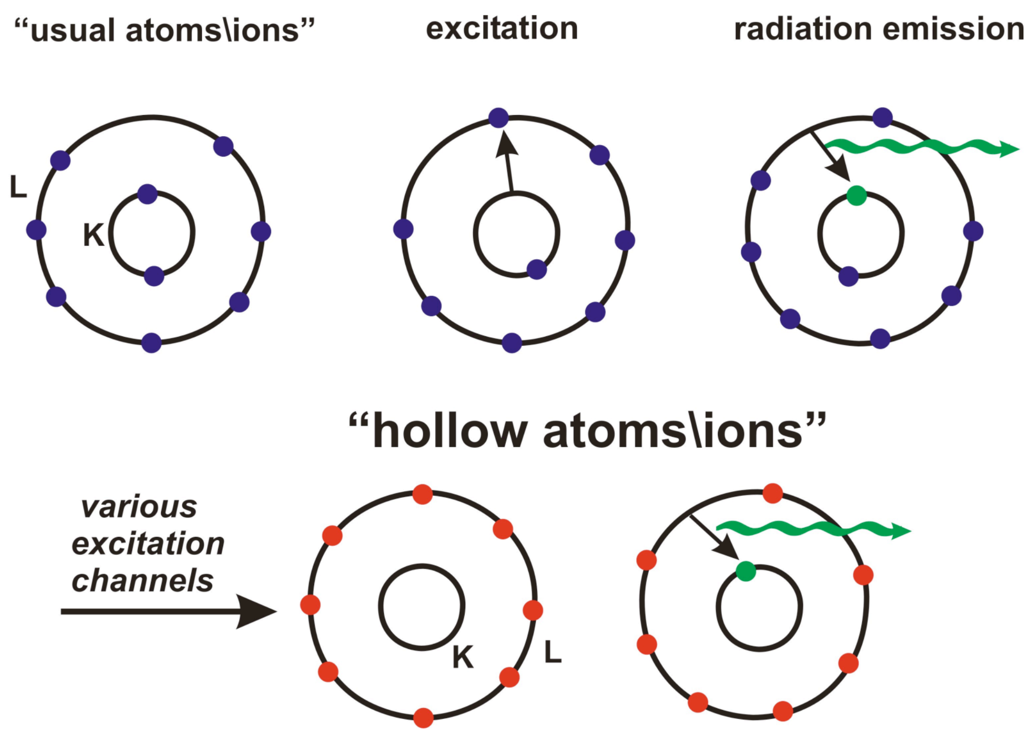
Hollow Ions I.



For hollow ions, the absorbing ground state is barely populated

No photoabsorption

An ideal probe of high density matter

- No radiative recombination regime
- Excellent time resolution, i.e. < 1 ps

in “usual” dense plasmas, the emission is not observable: below Bremsstrahlung

Hollow ions II.

- **Bound-bound opacity:**

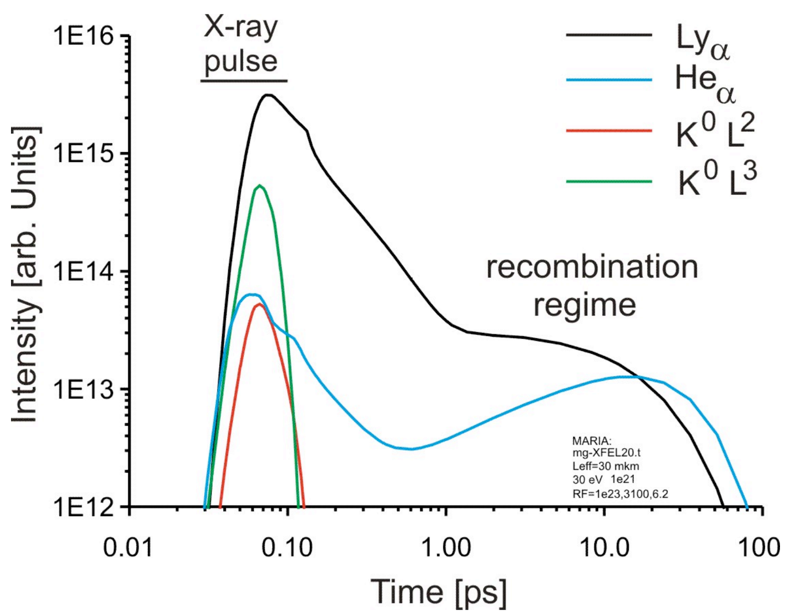
$$\tau_0(Ly_\alpha, He_\alpha) \approx 10^2 - 10^3$$
$$\tau_0(satellites) \approx 10^1$$

$n_e = 10^{23}\ cm^{-3}$, $kT_e = 300\ eV$, $L_{eff} = 30\ \mu m$:

$$I(observed) = I(emitted) \times \exp(-\tau)$$

Even for small source sizes and x-ray transitions opacity of resonance lines and satellites is a problem !

- **Temporal evolution:**



Transient simulations (MARIA):

- multi-level collisional-radiative kinetics
- ground states, single & double excited states + hollow ion states
- radiation field physics

The recombination regime is of importance !

Rosmej et al. HEDP **3**, 218 (2007)

FEL induced Hollow Ion X-Ray Emission

Inner-shell photoionization:

$$E_{X\text{-}FEL} = 3.1\ \text{keV} > E_i(1s^1)$$

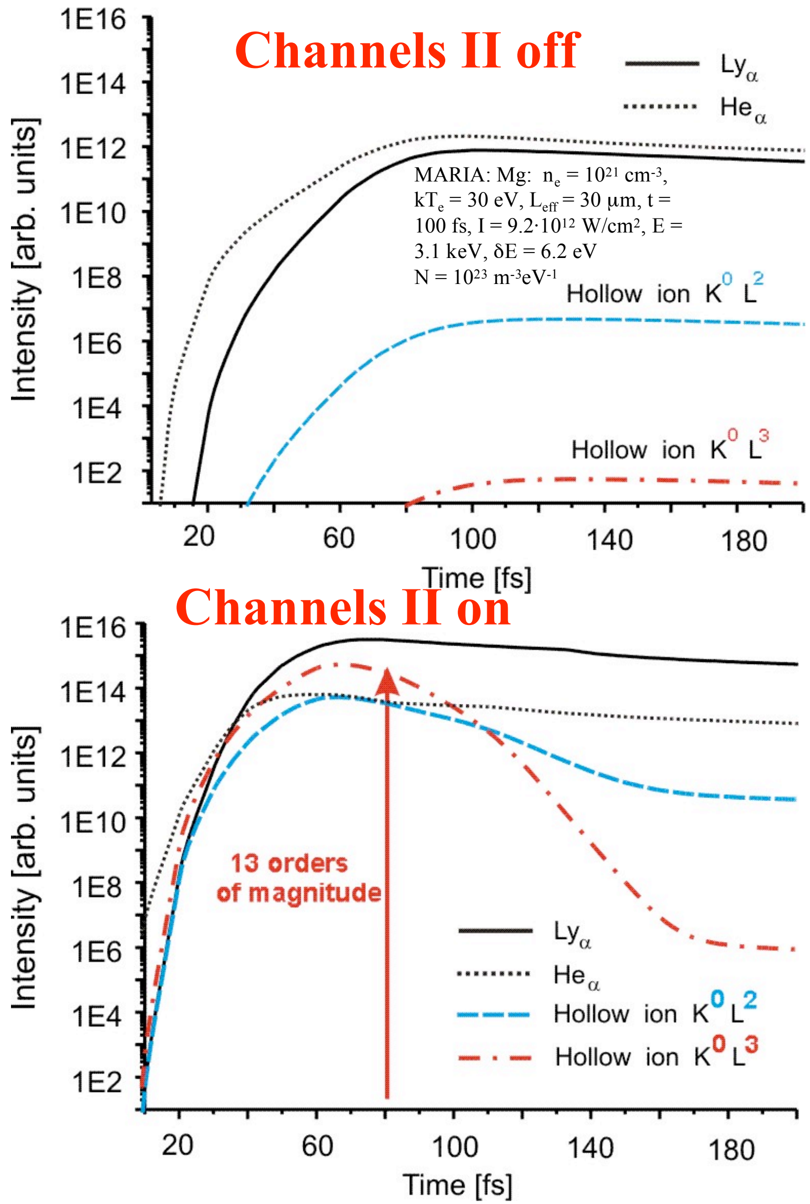
I. $K^2\, L^n + h\nu_{X\text{-}FEL} \rightarrow K^1\, L^n + e$

Relaxation time:
τ(autoionization) $\approx$ 50 fs

II. $K^1\, L^n + h\nu_{X\text{-}FEL} \rightarrow K^0\, L^n + e$

III. $K^0\, L^n \rightarrow K^1\, L^n + h\nu_{\text{Hollow Ion}}$

10 orders of magnitude will open up a new field of research



Rosmej, Lee, EPL **77**, 24001 (2007)

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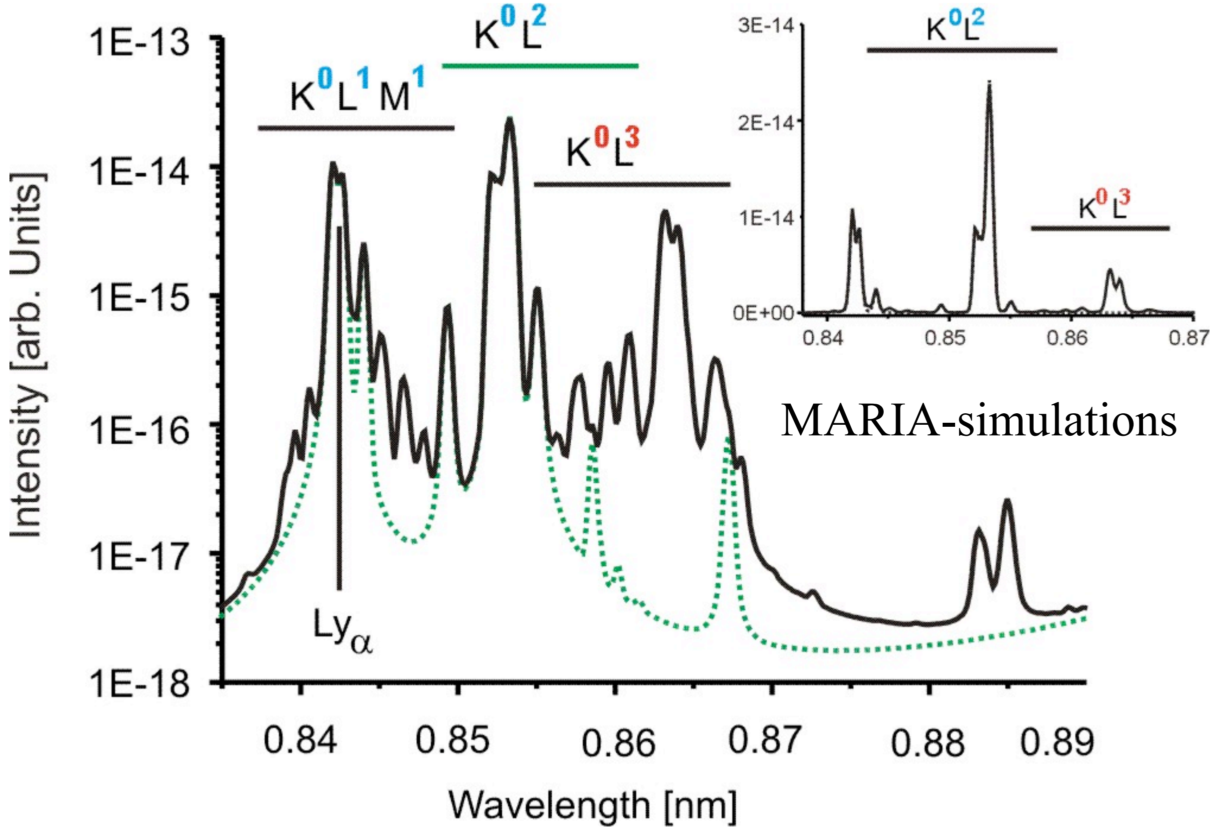
Hollow ion emission: observable time integrated ?



MARIA-simulations

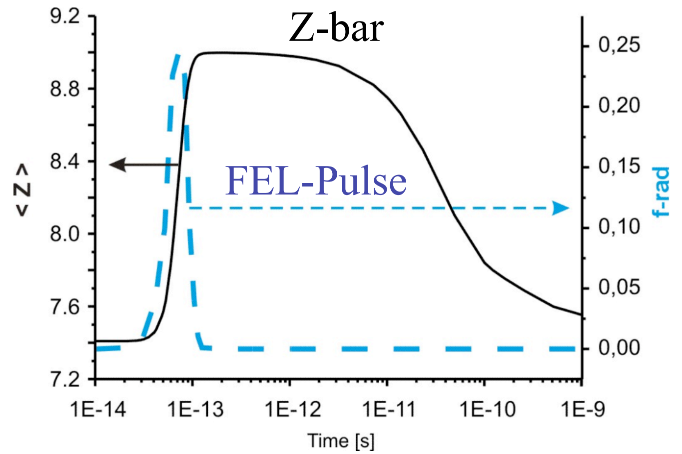
MARIA: Mg

$n_e = 10^{21}$ cm^{-3}, kT_e = 40 eV, L_{eff} = 10 μm

I = 5.3·10^{12} W/cm^2, E = 1.85 keV, δE = 6 eV

Hollow ion emission observable even in time integrated spectra

Hollow ion emission



The « intrinsic » time resolution probes the WDM/DSCP regime

Rosmej, Lee, EPL **77**, 24001 (2007)

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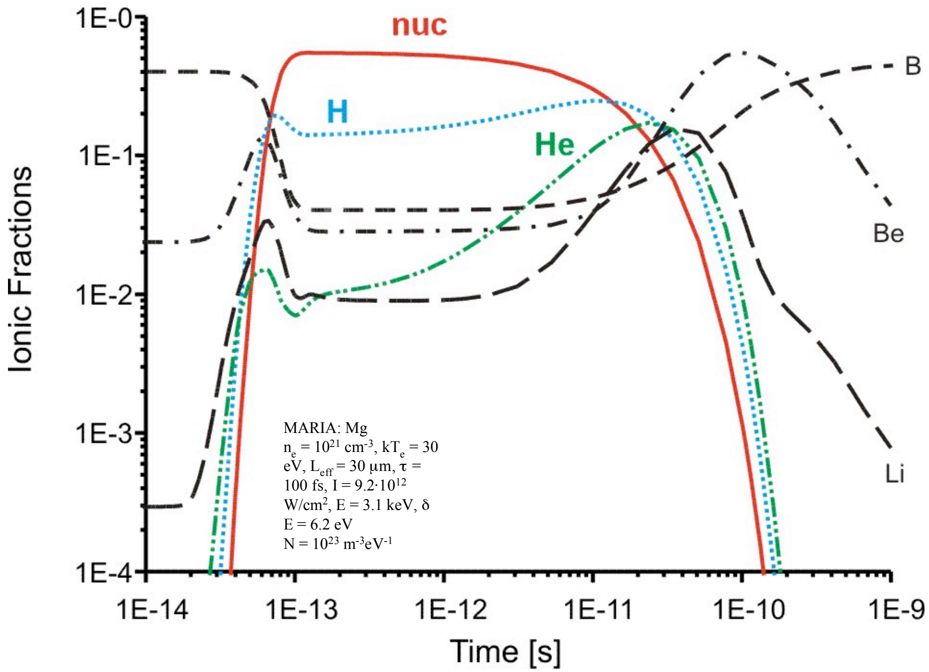
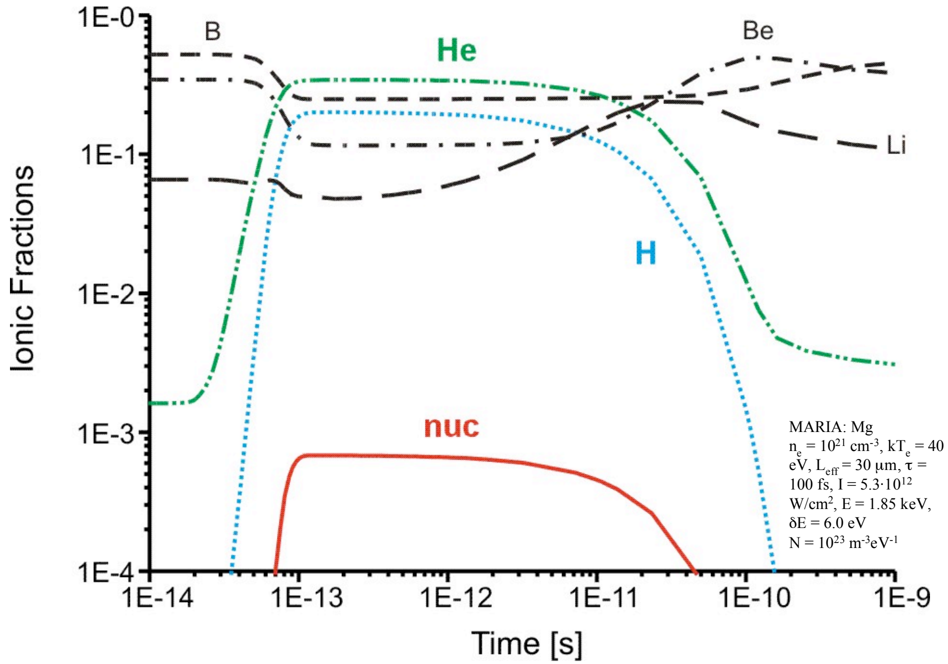
Selection of different ionization regimes I.

$E_{X\text{-}FEL} = 3.1\ \text{keV} > E_i(1s^1)$



overionized

$E_{X\text{-}FEL} = 1.85\ \text{keV} < E_i(1s^1)$



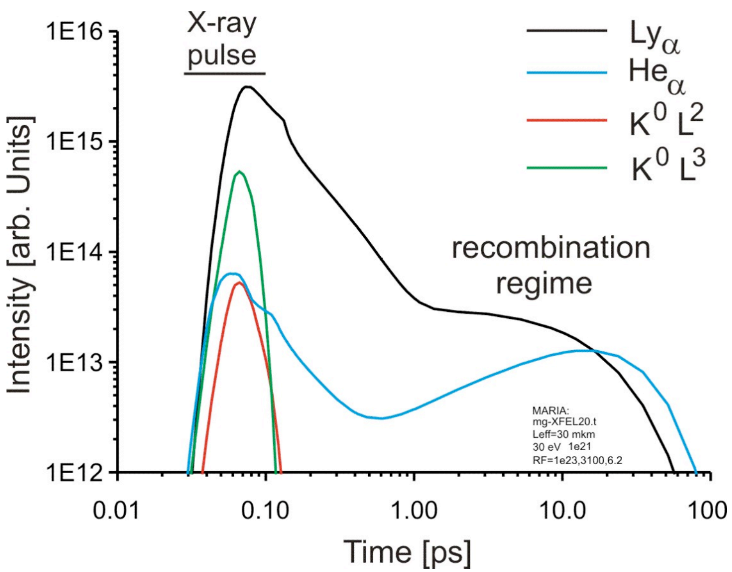
partially ionized

Rosmej, Lee, EPL **77**, 24001 (2007)

Selection of different ionization regimes II.

$E_{X\text{-}FEL} = 3.1 \text{ keV} > E_i(1s^1)$

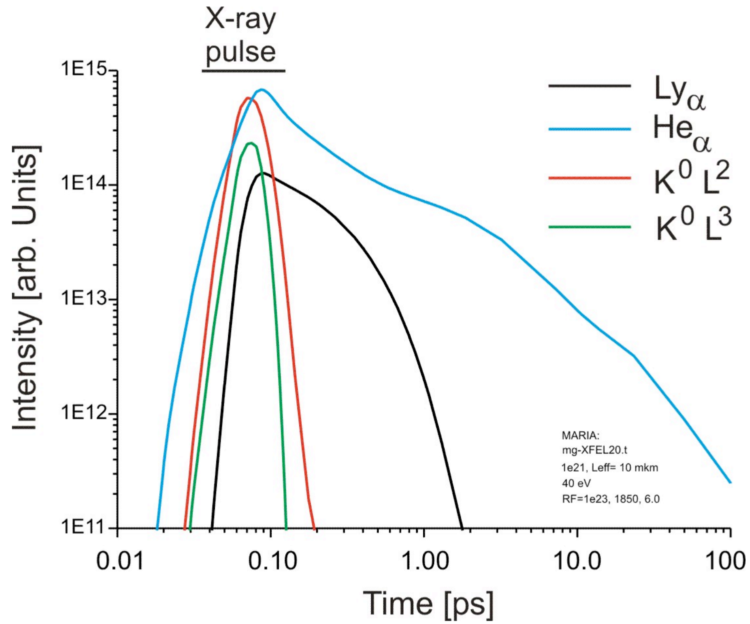
overionized



Strong recombination into H- and He-like ions

$E_{X\text{-}FEL} = 1.85 \text{ keV} < E_i(1s^1)$

partially ionized



Weak recombination into H- and He-like ions

Rosmej, Lee, EPL **77**, 24001 (2007)

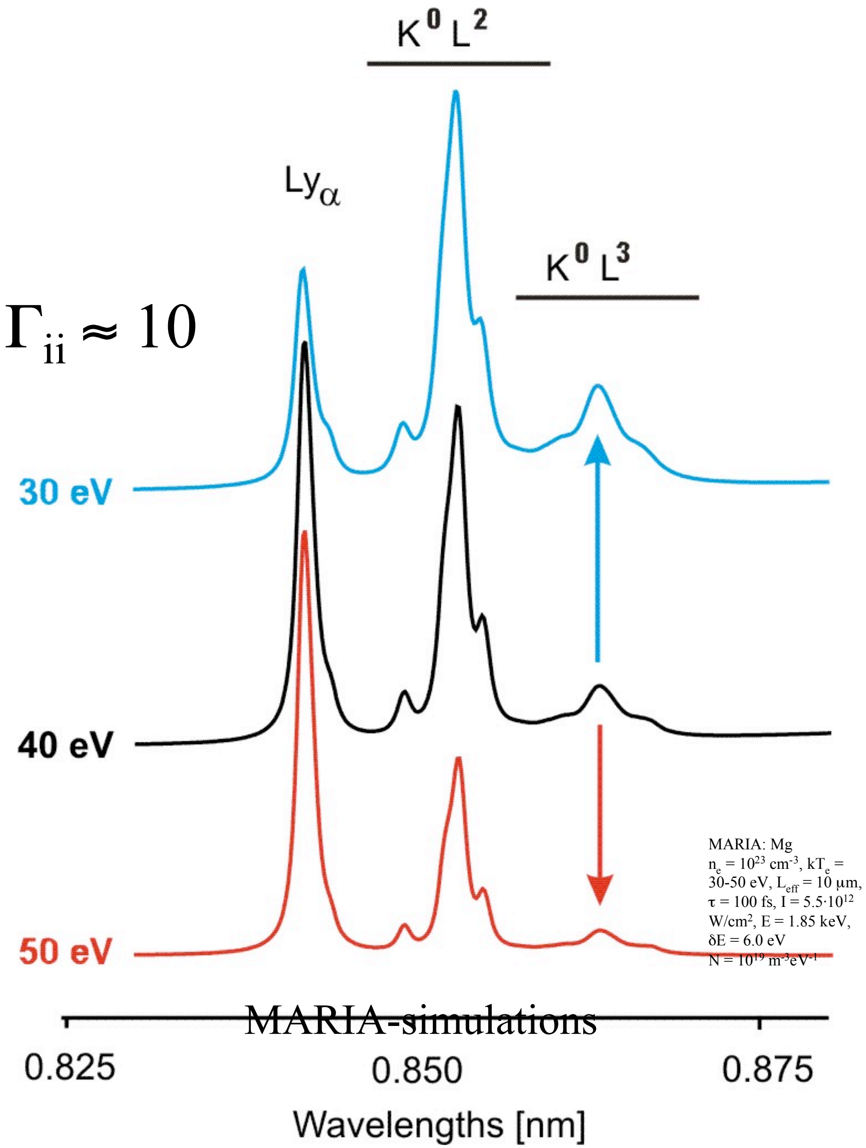
Hollow ion emission: temperature sensitivities

The independent determination of the temperature is one of the most important issues in WDM/DSCP research:

$$\Gamma_{ii} \propto \frac{Z^2 n_i^{1/3}}{T_i}$$

The hollow ion emission indicates the matter temperature near solid density

K^0L^N populations are related to the population densities K^2L^N : allows to test detailed ionization models



Rosmej, Lee, EPL **77**, 24001 (2007)

(not just the Z-bar but different charge state populations)

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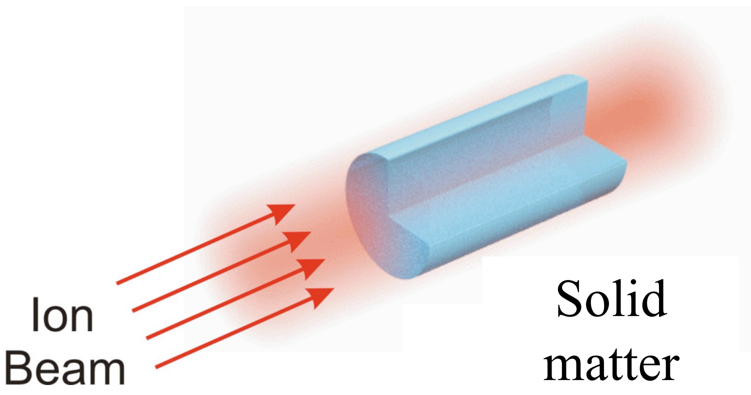
V. Heavy ion beams

Warm Dense Matter creation

Heavy ion beam heating of solid matter:

- **high beam intensities: WDM regime**
- well known energy input
- macroscopic samples (mm-size)
- hydro motion: $\tau(n,T) > ns$
- homogenous samples
  (Bragg peak outside the sample)
- accessible by diagnostics

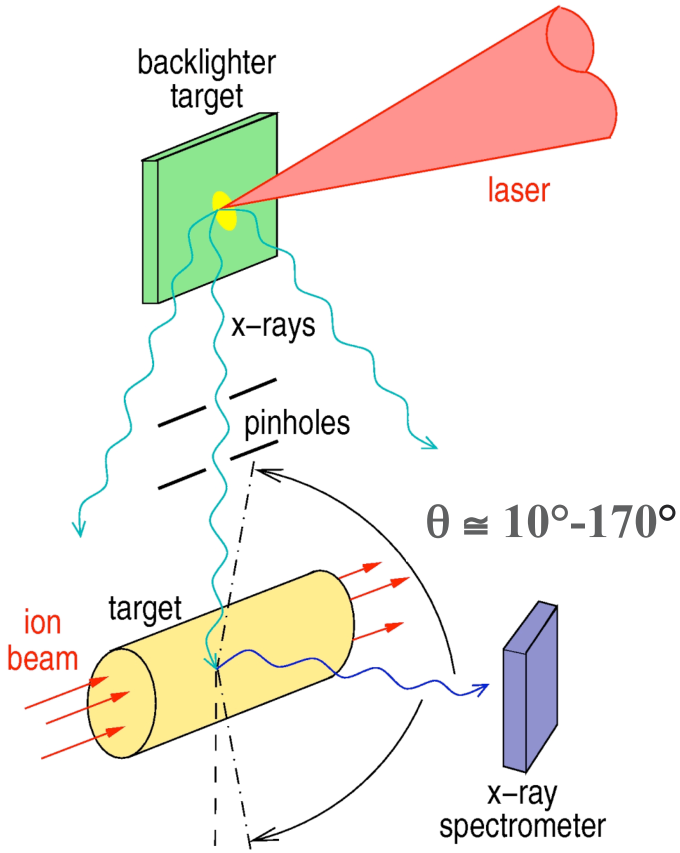


In contrast, lasers do have:
μm source size, fs-ps time scales, inhomogeneities, energy deposition is not very well known

The key point is:

WDM created that it can be well diagnosed

The key information is obtained from the kilojoule PHELIX driven x-ray scattering



Spectrally resolved x-ray scattering will allow to properly interprete measurements of material properties:

- Thermal and electrical conductivity
- Equation of state
- Opacity
- Atomic physics in dense plasmas

Small bandwidth x-ray source:

- He_α-transition of, e.g., titanium, 4.75 keV

Laser parameters:

- time resolution (ns): pulse << hydro
- energy: some kJ (photon need !)

X-ray scattering for WDM produced by heavy ions beams at GSI has been proposed (Riley & Rosmej 2003, GSI Annual report), is now adopted by several experiments.

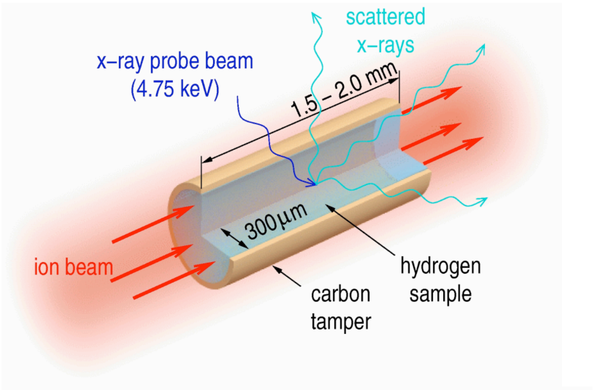
http://www-aix.gsi.de/plasma2003
http://www.gsi.de/phelix/Experiments/FAIR/WDM/index.html

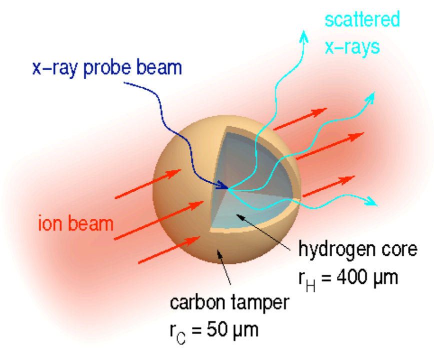
WDM-collaboration at GSI/FAIR

WDM

« Radiative properties of Warm Dense Matter produced by intense heavy ion beams »

www.gsi.de/forschung/phelix/Experiments/FAIR/WDM/index.html



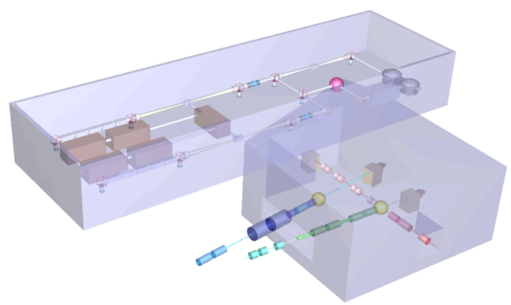


Target design + X-ray scatter:

An. Tauschwitz, J.A. Maruhn, D. Riley, G. Shabbir Naz, F.B. Rosmej, S. Borneis, A. Tauschwitz : "Quasi-isochoric ion beam heating using dynamic confinement in spherical geometry for X-ray scattering experiments in WDM regime", High Energy Density Physics **3**, 371 (2007)

GSI-Darmstadt, Germany
Johann Wolfgang Goethe Universität, Frankfurt, Germany
Max-Planck Institut für Kernphysik, Heidelberg, Germany
University of Rostock, Institute of Physics, Rostock, Germany
Université Pierre et Marie Curie (UPMC), Paris, France
LULI-PAPD, Paris, France
Université de Provence, Centre St. Jérôme, PIIM, Marseille, France
LOA-ENSTA, Palaiseau, France
Queens University of Belfast QUB, Belfast, UK
Fudan University, Shanghai
LANL, Los Alamos, USA
LLNL, Livermore, USA
UCLA, Los Angeles, USA
Institute of Laser Engineering ILE, Osaka, Japan
The Institute of Physical and Chemical Research RIKEN, Saitama, Japan
Russian Research Center Kurchatov Institute, Moscow, Russia
Keldysh Institute of Applied Mathematics, Moscow, Russia
MISDC VNIFFTRI, Mendeleevo, Russia
ITEP, Moscow, Russia
Lebedev Physical Institute, Laboratory of Optics, Moscow, Russia
Lebedev Physical Institute, Thermonuclear Target Laboratory, Moscow, Russia
State Polytechnic University of St. Petersburg, Plasma Physics Laboratory, Russia

Laser design + Civil construction:



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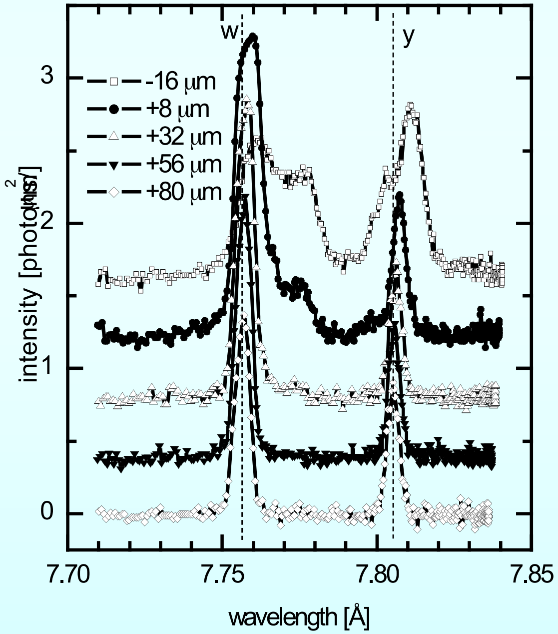
Conclusion and Outlook

- Atomic physics in dense plasmas: challenging field of research
- Development of good samples and unambiguous diagnostics: key goal

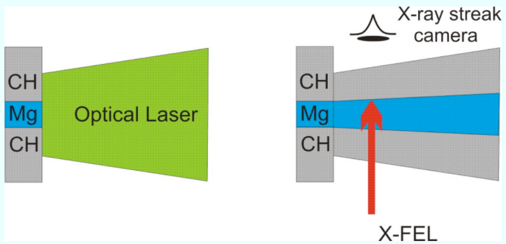
- *Benchmark of radiative properties: high resolution spectroscopy*

LULI



Shift of exchange energy (spin) in dense plasmas

FEL: Hollow ions

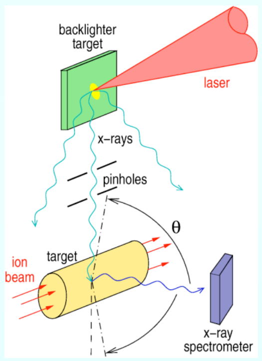


10 orders of magnitude more intense than in usual plasma sources

New field of research:

- Atomic physics
- Diagnostic (τ_0, fs, …)
- Dense plasma models

Heavy Ion Beam + PHELIX



- X-ray scattering,….
- XANES, EXAFS,…

Plasma Physics proposals at GSI

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