Joint U.S. Russia Conference
on Advances in Materials Science
Prague, August 30 – September 4, 2009

Strongly Coupled Plasma Nanochannel Created by a Fast Single Ion in Condensed Matter

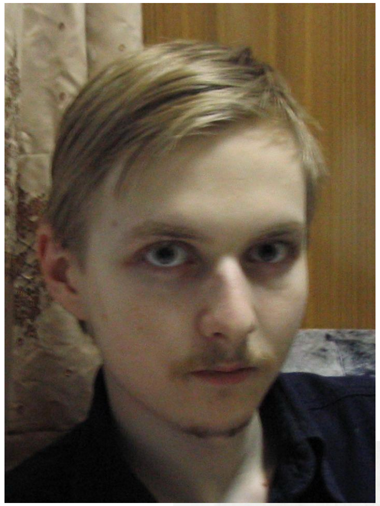
Genri Norman

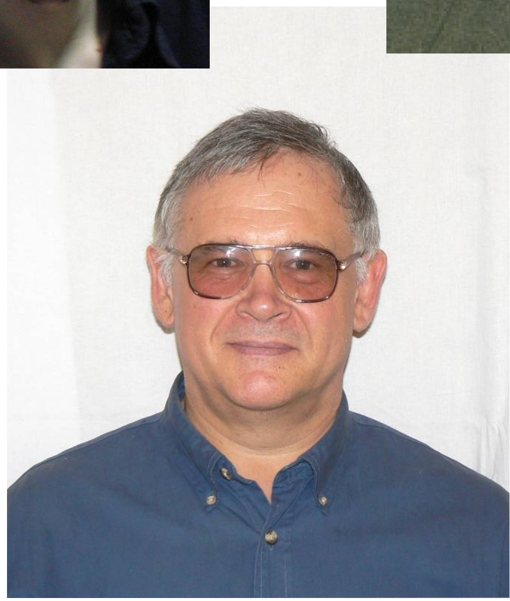
Joint Institute for High Temperatures of Russian Academy of Sciences

Moscow Institute of Physics and Technology

Theorists

A.V.Lankin, I.V.Morozov, I.Yu.Skobelev





A.Ya. Faenov, S.A. Pikuz Jr.

Experimentalists

Extended title

Excited state of warm dense matter

or

Exotic state of warm dense matter

or

Novel form of warm dense matter

or

New form of plasma

Three sources of generation

Fast Single Ions A.V.Lankin, I.V.Morozov, G.E.Norman, S.A. Pikuz Jr., I.Yu.Skobelev
***Solid-density plasma* nanochannel generated by a fast single ion in condensed matter**
Physical Review E 79, Issue 3, 036407 (13 pp) (2009)

Laser J.Wark. ***Saturable absorption of intense XUV radiation, and a novel form of warm dense matter***
Plenary talk at 36th EPS Conference on Plasma Physics, June 29 - July 3, 2009, Sofia, Bulgaria.
B.Nagel *et al*. (54 coauthors) Nature Physics (2009)

Exploding wires G.E. Norman, V.V. Stegailov, A.A. Valuev. ***Nanosecond Electric Explosion of Wires: from Solid Superheating to Nonideal Plasma Formation***
Contrib. Plasma Phys., V. 43. P. 384-389 (2003)

similarity:

solid state density, two temperatures:
electron temperature about *tens* eV,
cold ions keep original crystallographic positions,
but electron band structure and phonon dispersion are changed,

transient but steady (quasi-stationary for a short time) state of non-equilibrium, uniform plasmas (no reference to non-ideality, both strongly and weakly coupled plasmas can be formed)

spectral line spectra are emitted by ion cores embedded in plasma environment which influences the spectra strongly,

lifetime limiting processes:
electron-phonon exchange, recombination, collisional electron cooling.

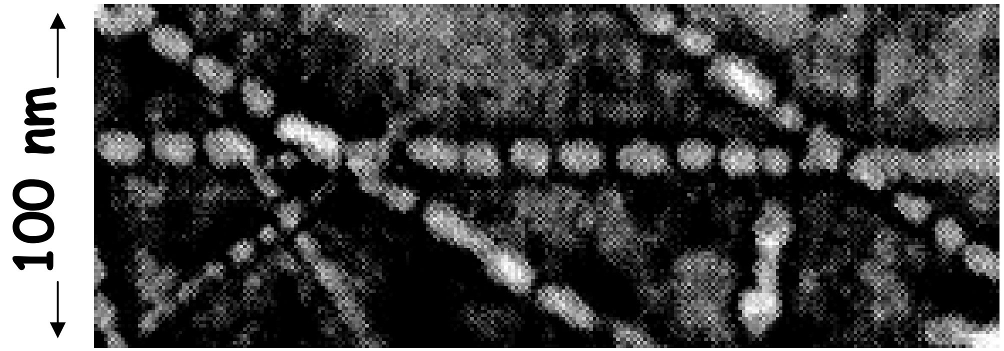
Diversity is considered in the conclusion

Motivation

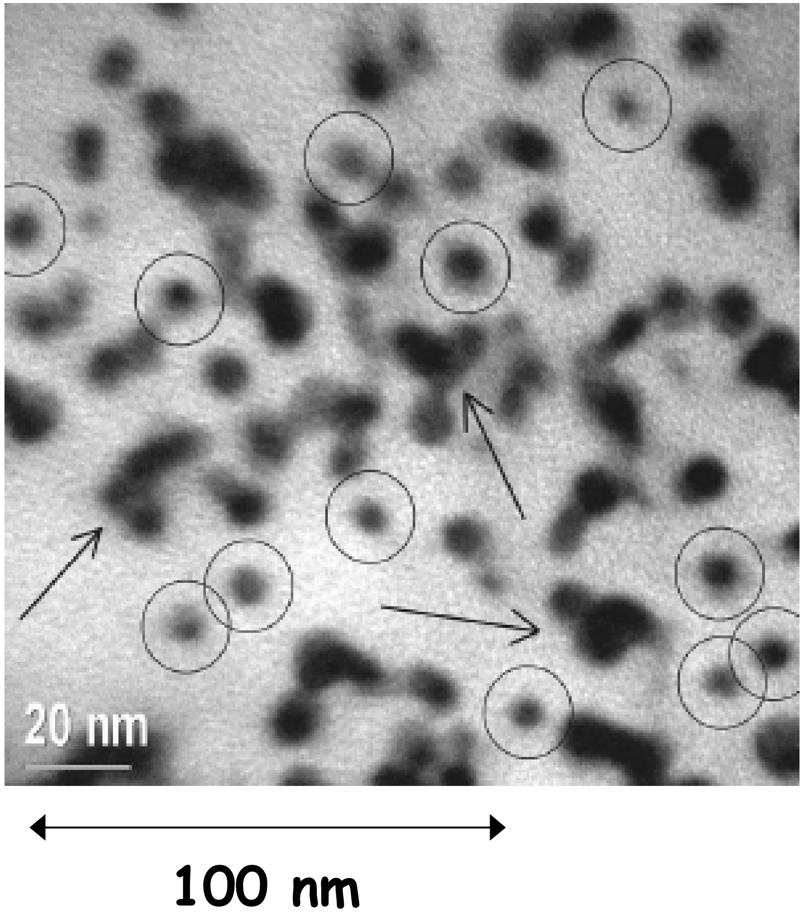
aging of fissible material

$$^{235}U + n^0 \rightarrow {}^{94}Rb + {}^{138}Cs + 3n^0$$

Defect formation



Motivation



Ion implantation into semiconductors

3 Mev/μ Au ion tracks
in Indium Phosphide

// A. Kamarou et al., PRB, 2006

Motivation

Cancer therapy

GSI, Darmstadt – 1000 patients / year
ITEP, Moscow – 100 patients / year

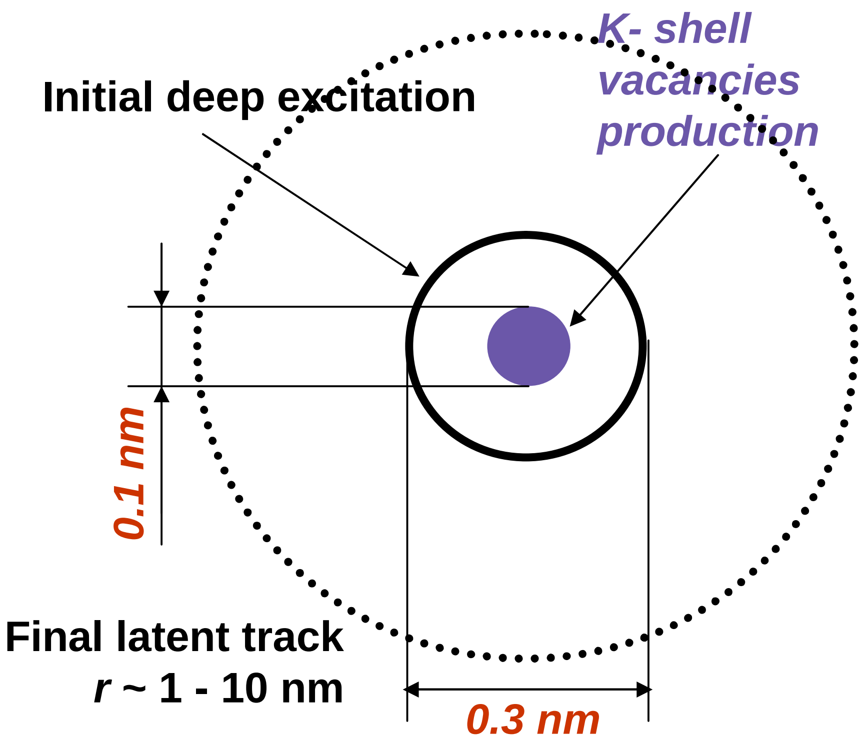
Contents

- Space and time scales
- X-ray spectroscopy data
- Plasma model suggested
- Self-consistence of the model
- Conclusions

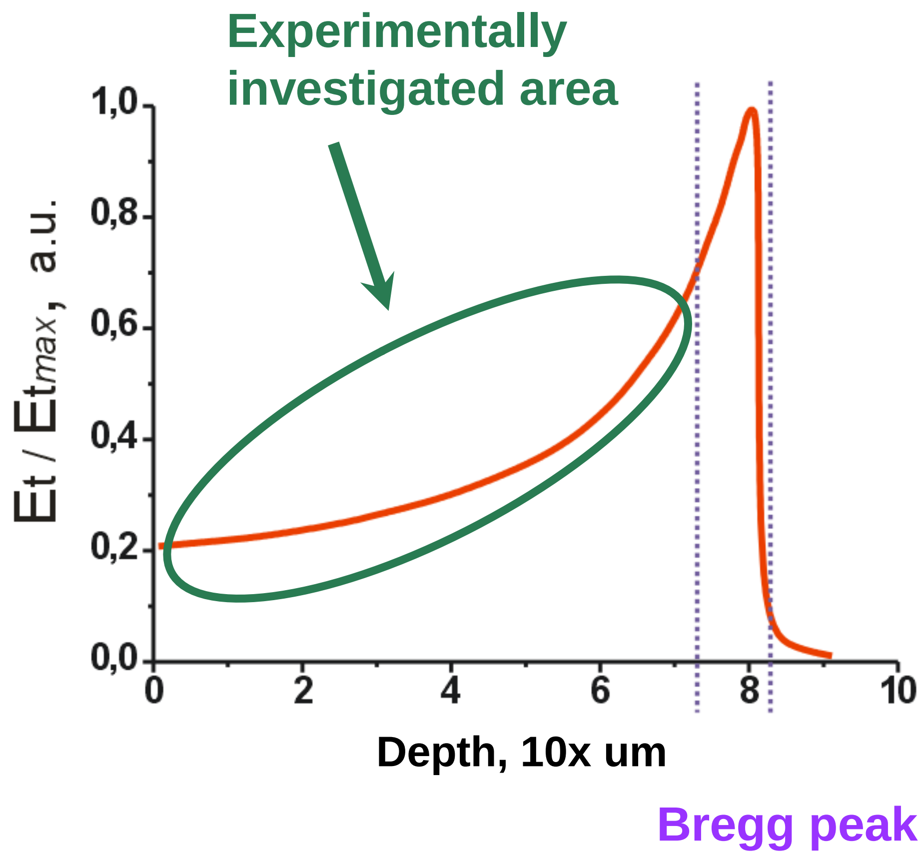
SPACE AND TIME SCALES

Spatial scales

Perpendicular to the track axis



Along the axis – stopping range

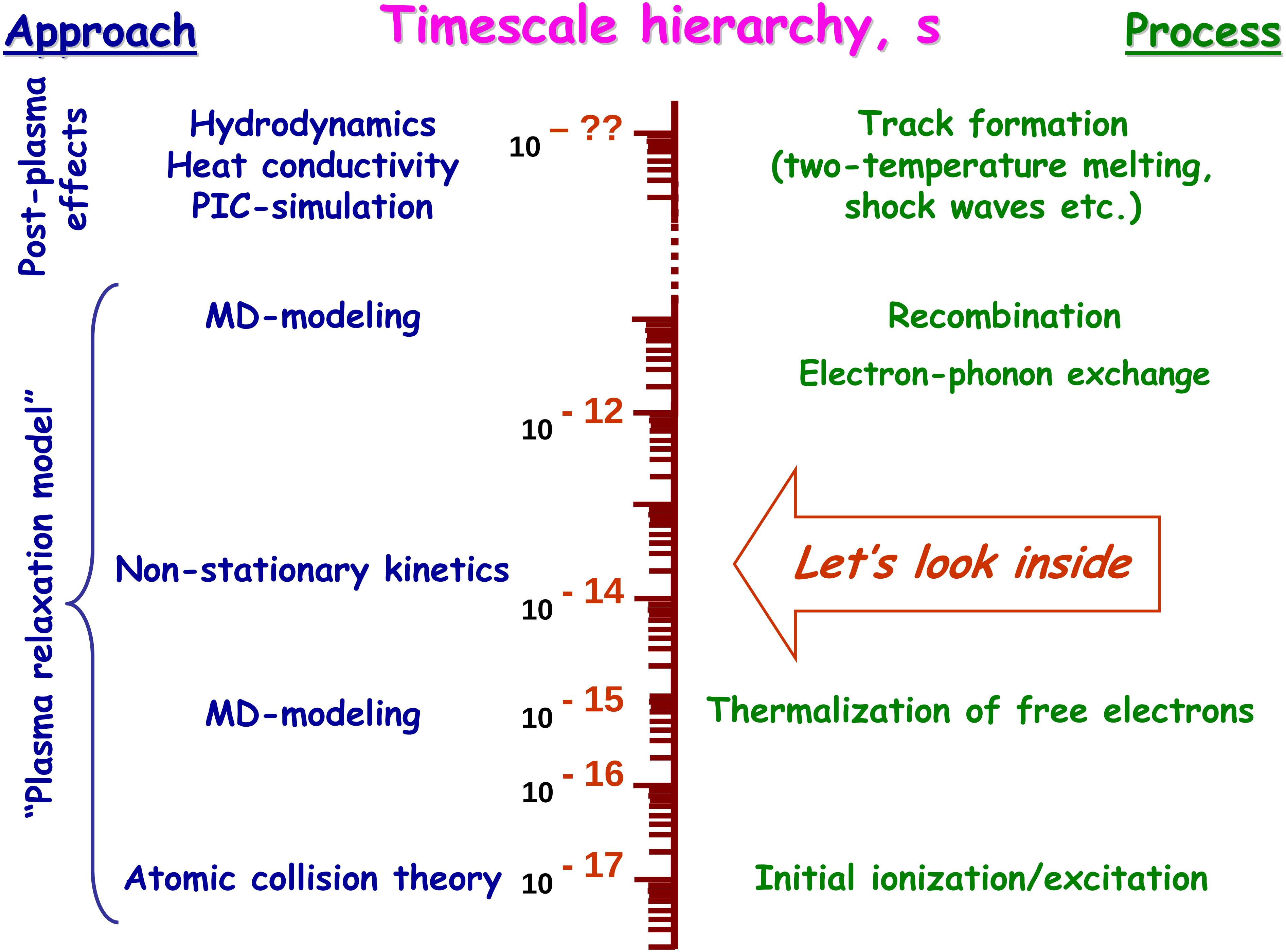


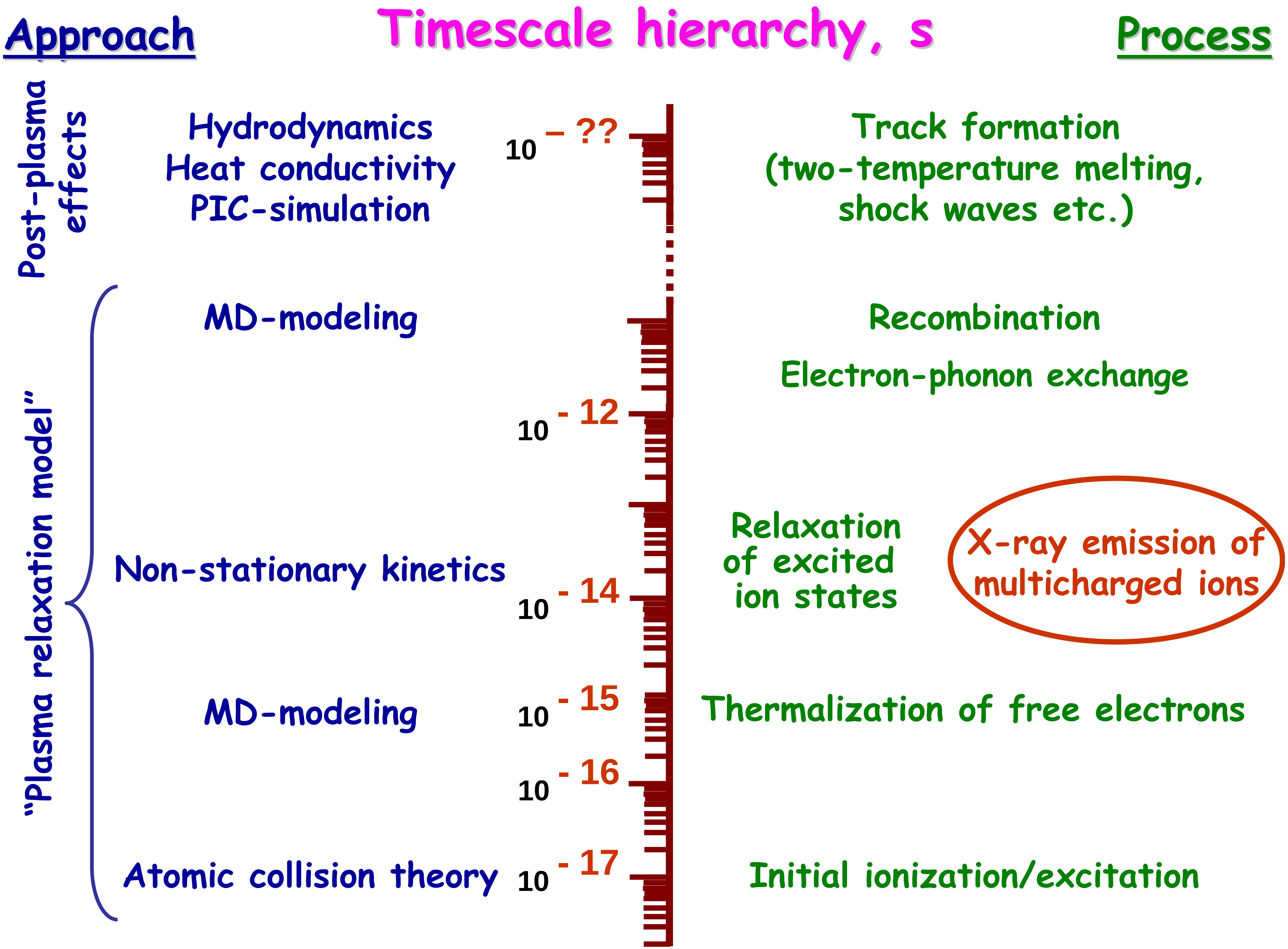
The main idea is in looking <u>inside</u> the heavy ion track <u>immediately after</u> the ion interacts with a target

Timescale hierarchy, s

Approach		Timescale hierarchy, s	Process
Post-plasma effects	Hydrodynamics Heat conductivity PIC-simulation	$10^{-??}$	Track formation (two-temperature melting, shock waves etc.)
"Plasma relaxation model"	MD-modeling		Recombination Electron-phonon exchange
		10^{-12}	
	Non-stationary kinetics	10^{-14}	Relaxation of excited ion states
	MD-modeling	10^{-15}	Thermalization of free electrons
		10^{-16}	
	Atomic collision theory	10^{-17}	Initial ionization/excitation

Timescale hierarchy, s



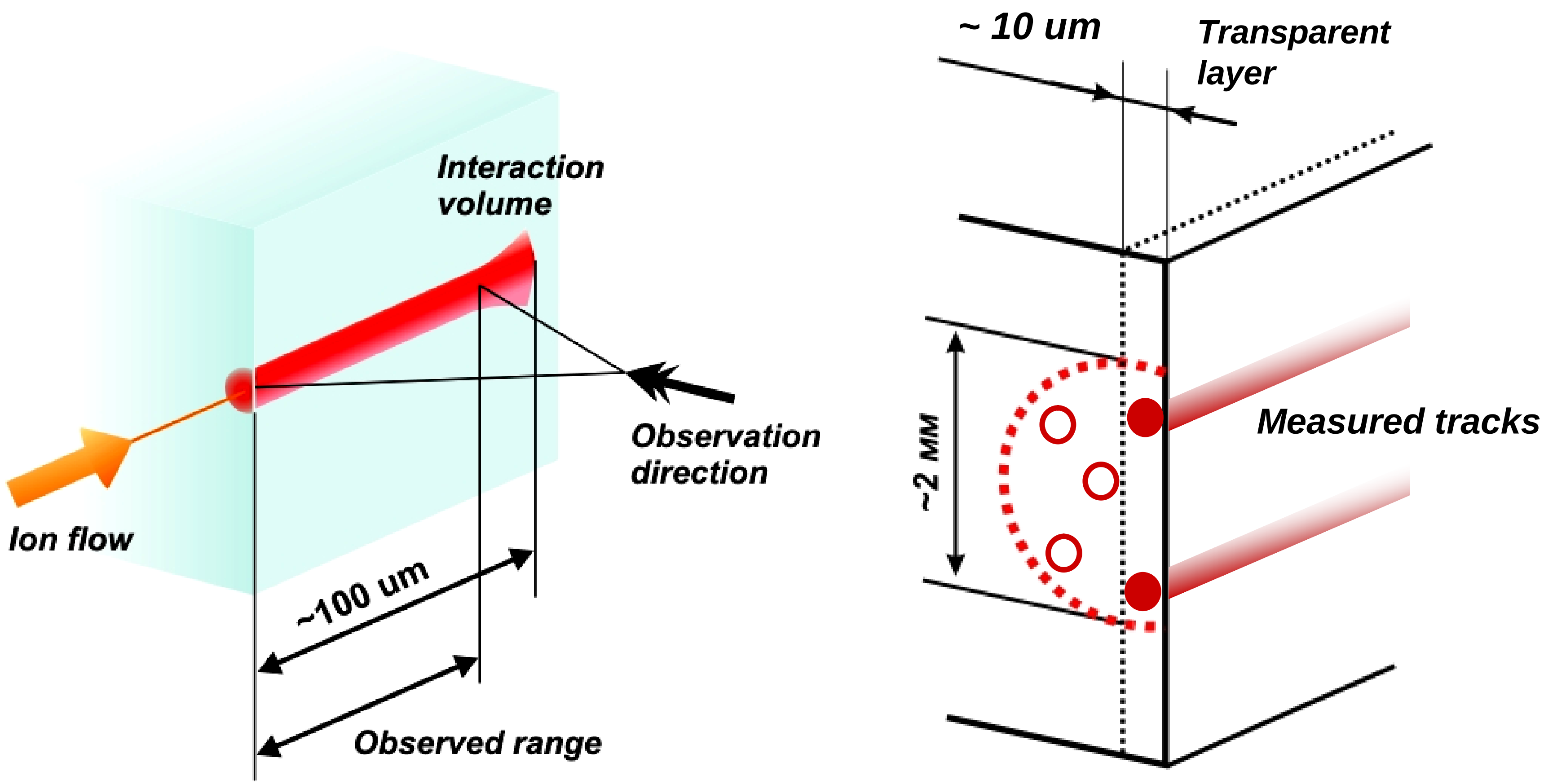

Approach
Timescale hierarchy, s
Process
Post-plasma effects
Hydrodynamics
Heat conductivity
PIC-simulation
$10^{-??}$
Track formation
(two-temperature melting,
shock waves etc.)
"Plasma relaxation model"
MD-modeling
Recombination
Electron-phonon exchange
10^{-12}
Non-stationary kinetics
10^{-14}
Relaxation
of excited
ion states
X-ray emission of
multicharged ions
MD-modeling
10^{-15}
Thermalization of free electrons
10^{-16}
Atomic collision theory
10^{-17}
Initial ionization/excitation

X-RAY SPECTROSCOPY EXPERIMENTAL DATA

D.H.H. Hoffmann, O. Rosmej, A. Blazevic, S. Korostiy, A Fertman , S.A. Pikuz Jr. ,V.P. Efremov ,

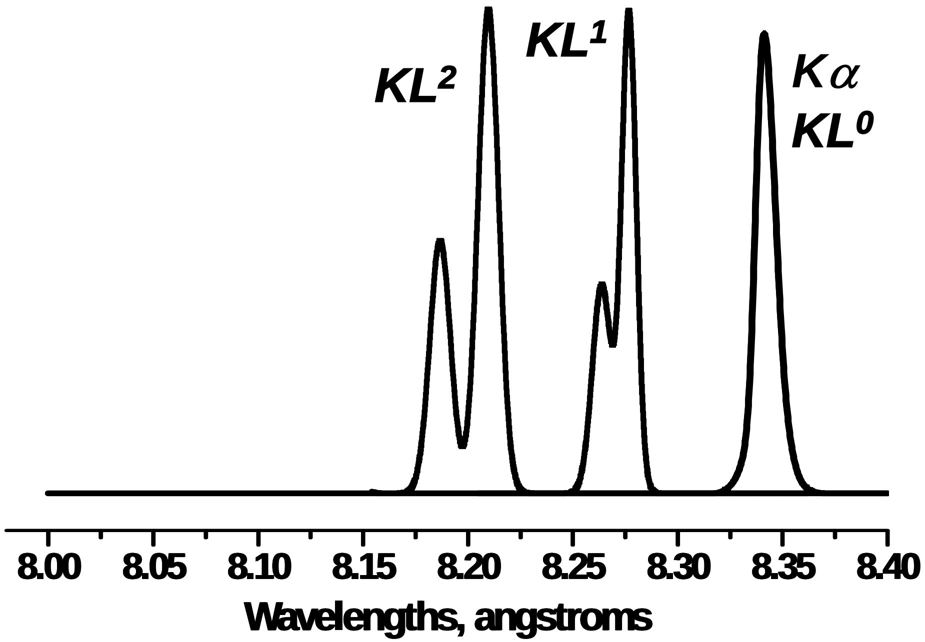
Gesellschaft fur Schwerionenforschung GSI, Darmstadt, Germany
Technical University, Darmstadt, Germany
Institute of Experimental and Theoretical Physics, Moscow, Russia
Joint Institute for High Temperatures RAS, Moscow, Russia

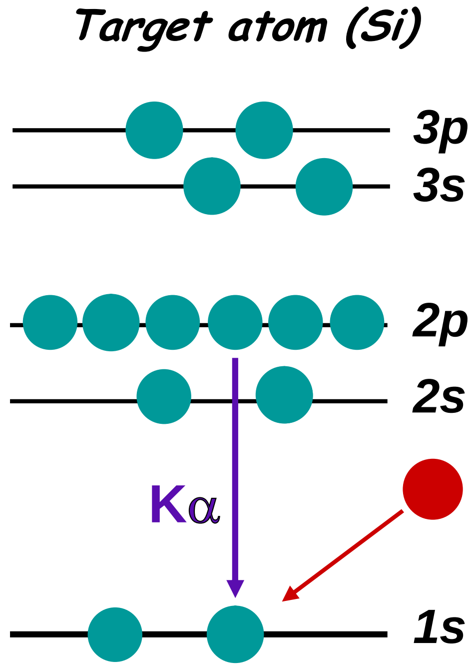
Low-current ions flow



Every following ion in the low-current beam interacts with the cold area of a target (wasn't' excited before or already has fully relaxed) and makes a contribution to the statistics of independent acts of single ions which propagate in solid media

Characteristic radiation



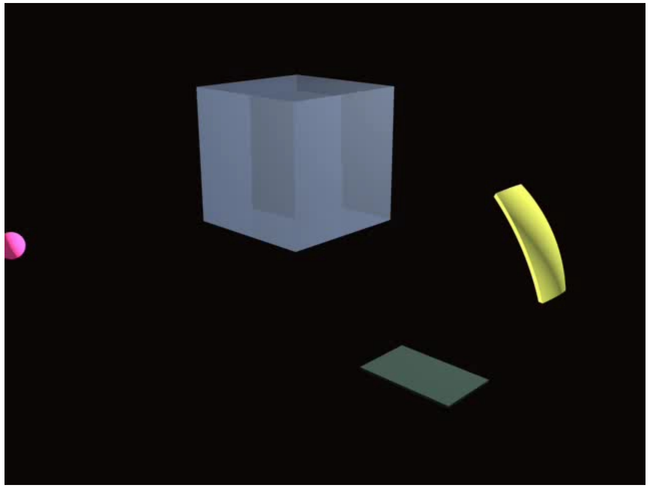


Times of radiation transitions:

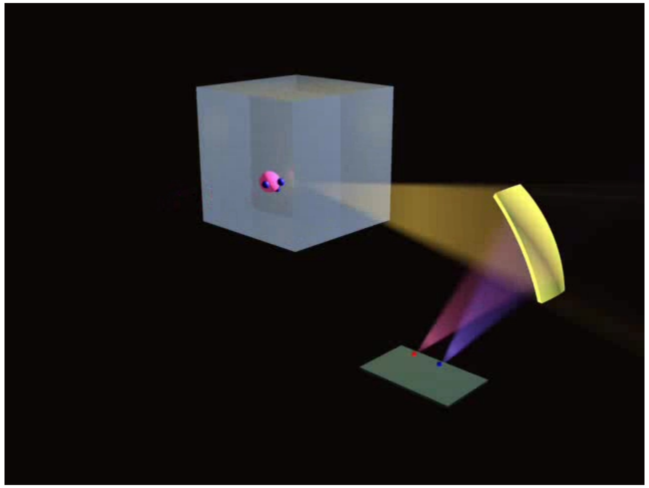
20-40 fs for ions with L-shell vacancies

Wavelength range:

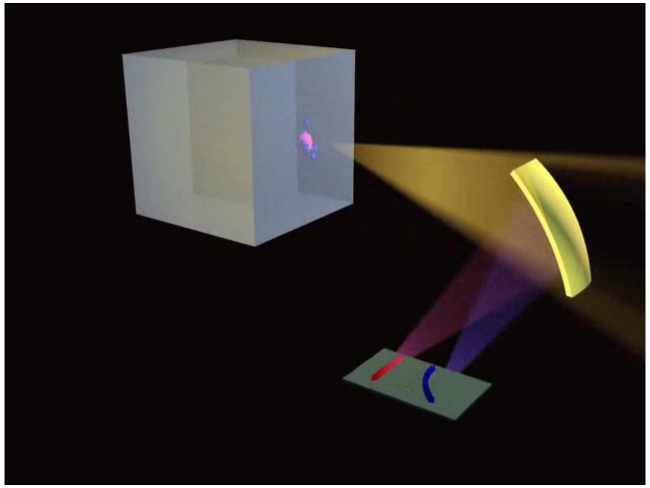
6.70 – 7.12 Å for Si
7.85 – 8.35 Å for Al



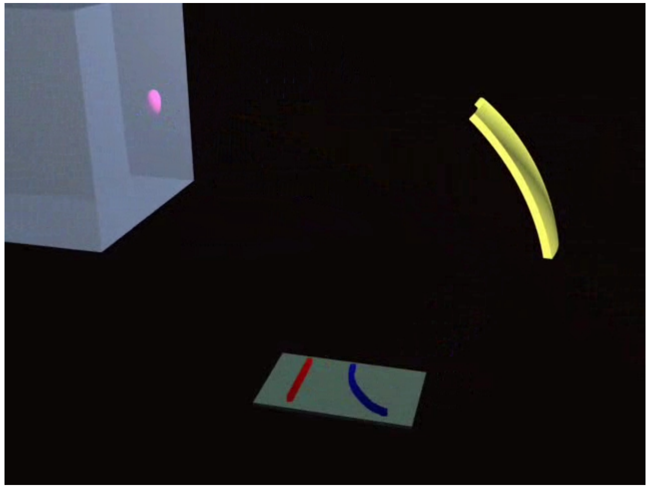
t_0



$t_1 > t_0$

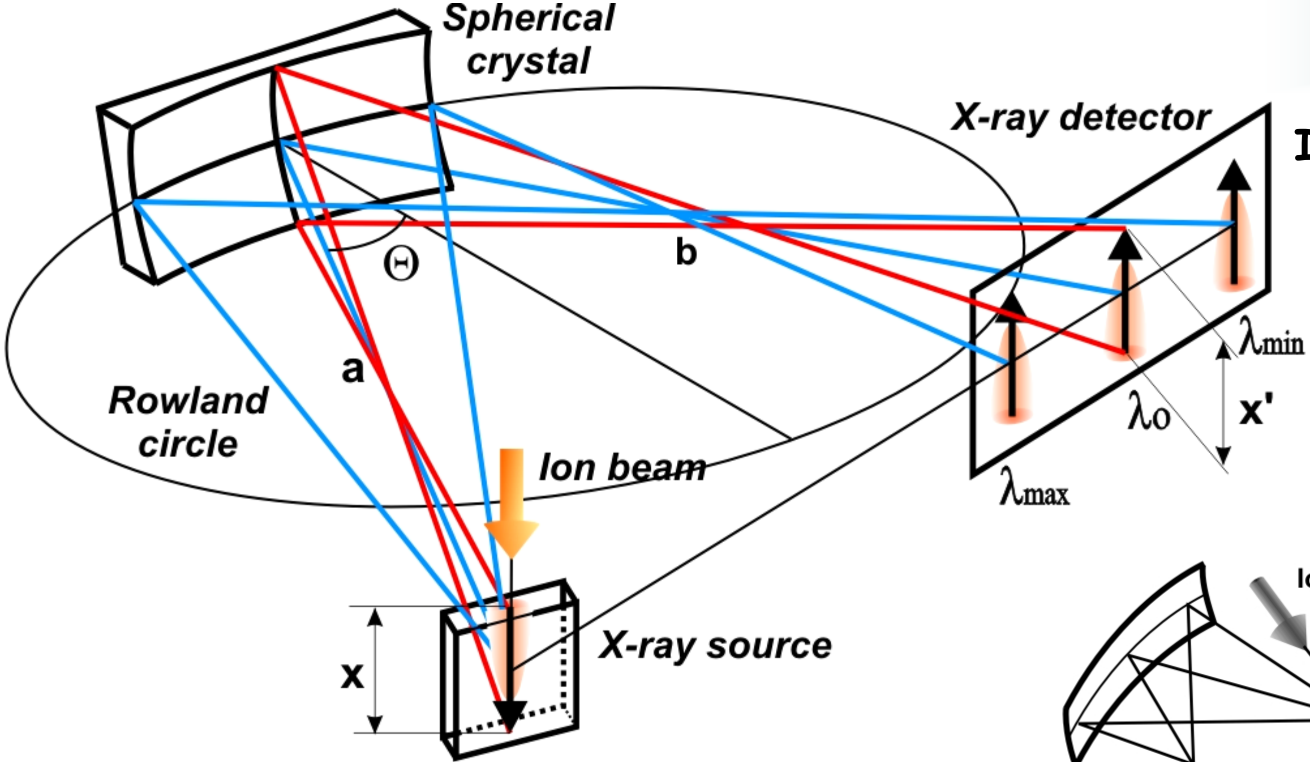


$t_2 > t_1$



$t_3 > t_2$

Experimental setup (GSI, Darmstadt, Germany)

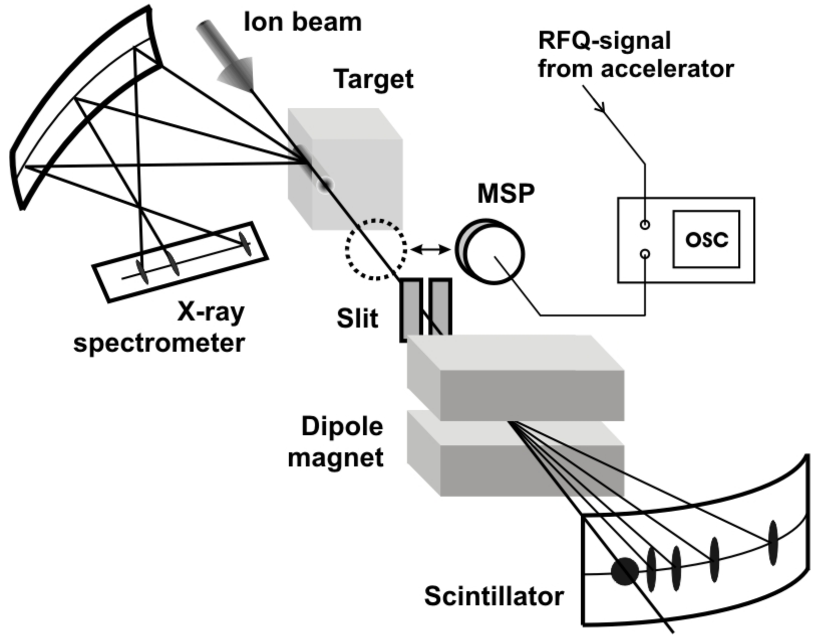


Beam parameters

Ions: Ni(58),Ca(48),Mg(26)

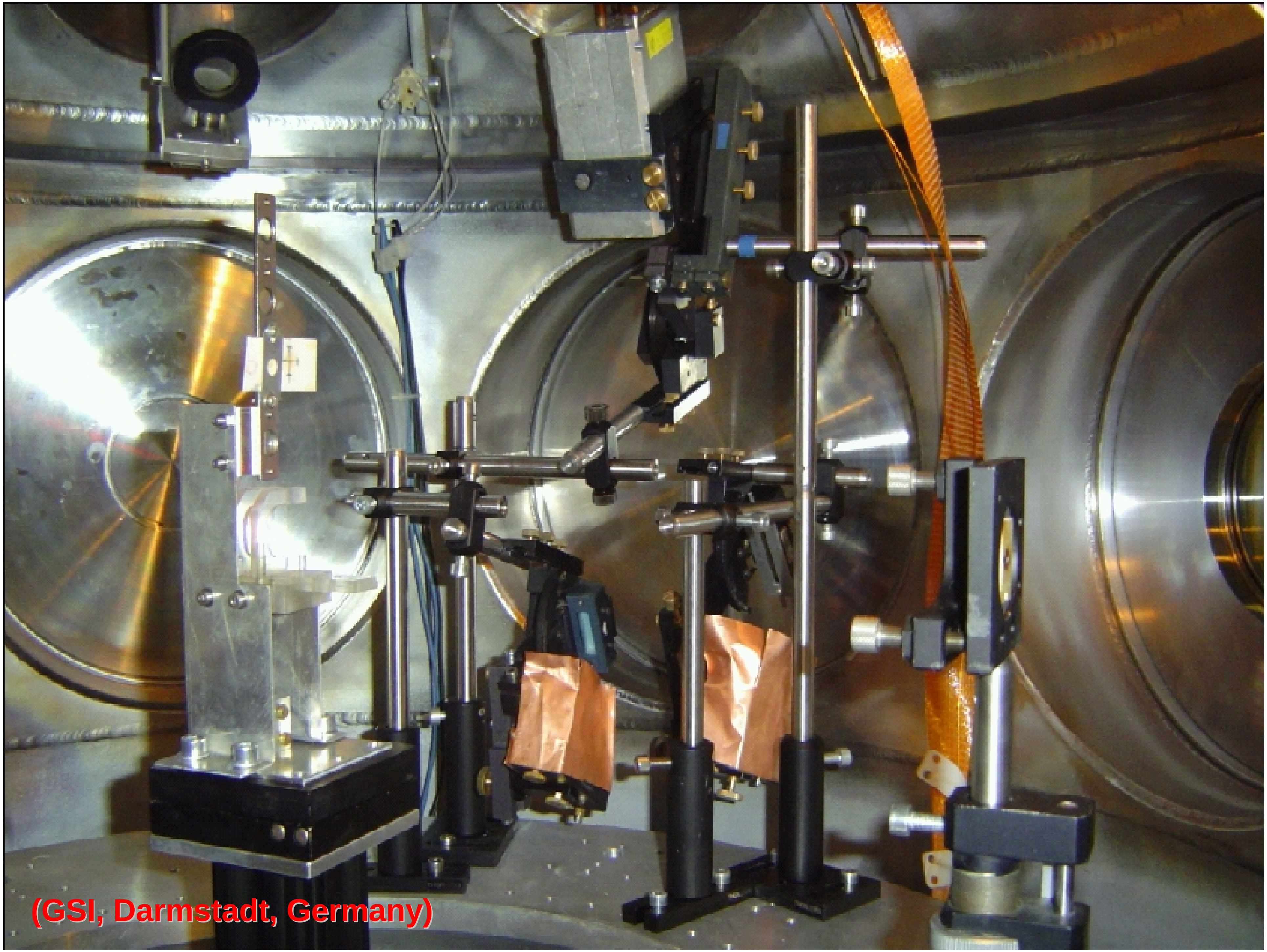
Current 0.1-1 uA

Energy: 4.7-11.4 MeV/u



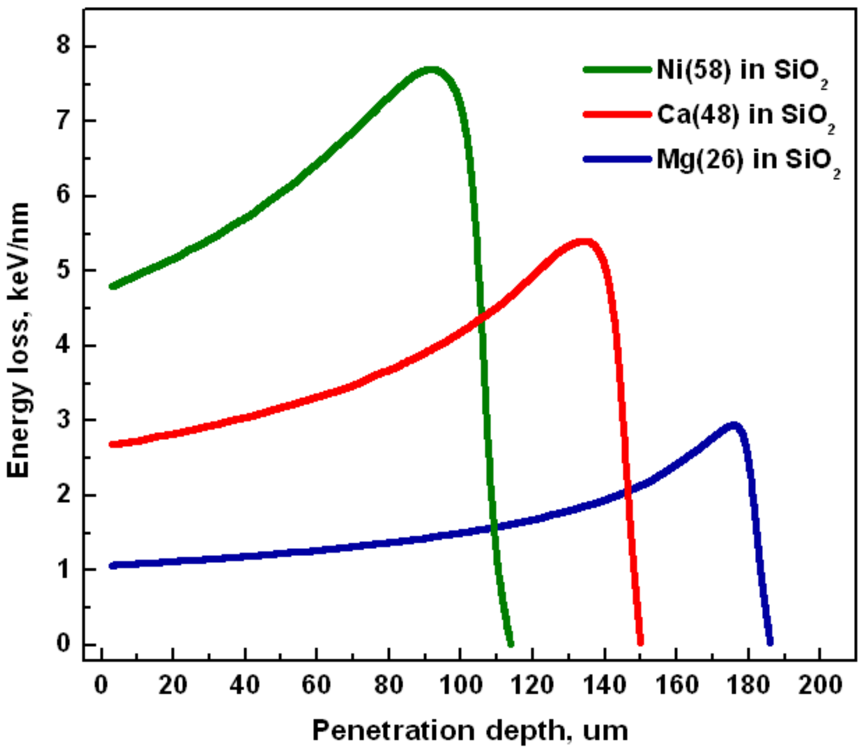
FSSR parameters

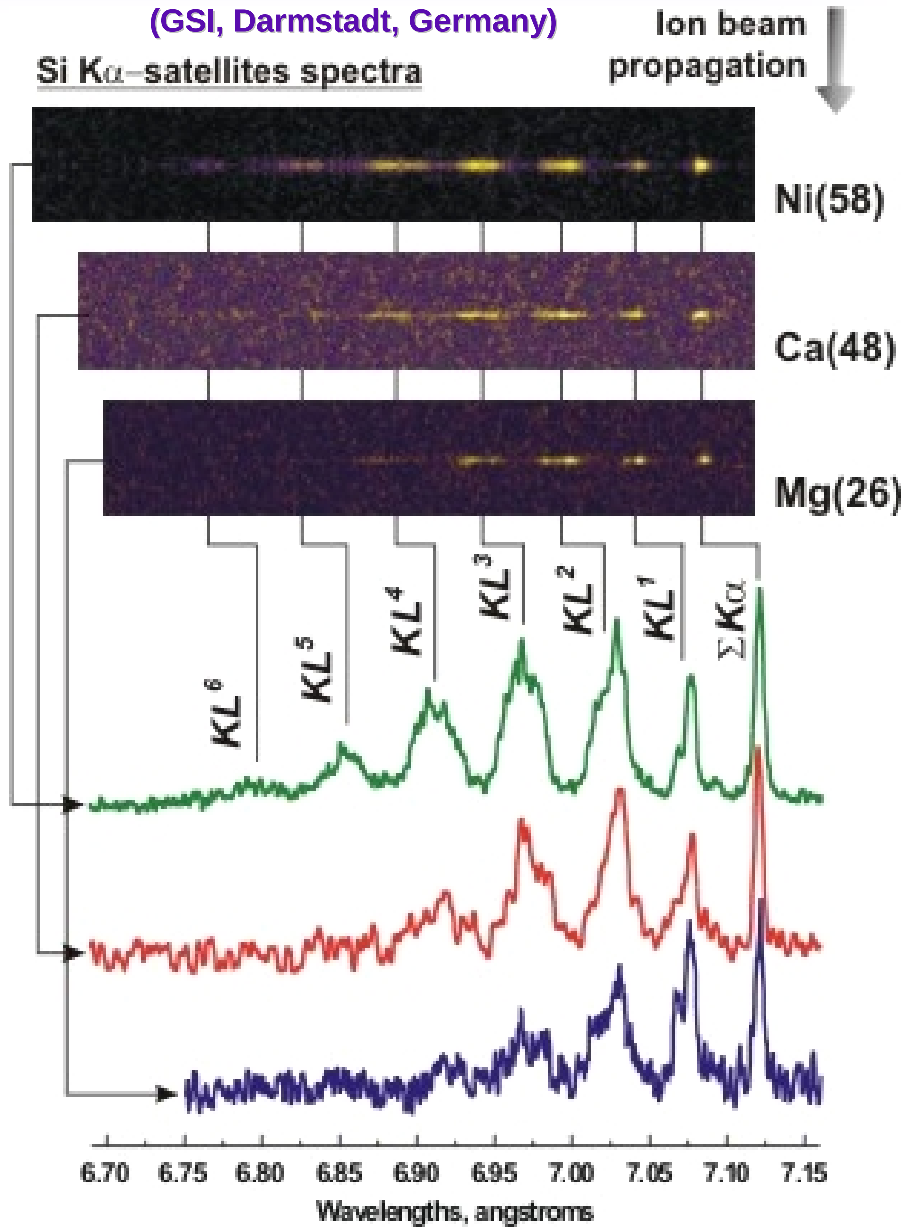
- Spectral resolution $\lambda/\delta\lambda = 10^3 - 10^4$
- Spatial resolution $\delta x = 5 - 10\ \mu m$
- High luminosity and tunable



(GSI, Darmstadt, Germany)

Influence of specific deposited energy

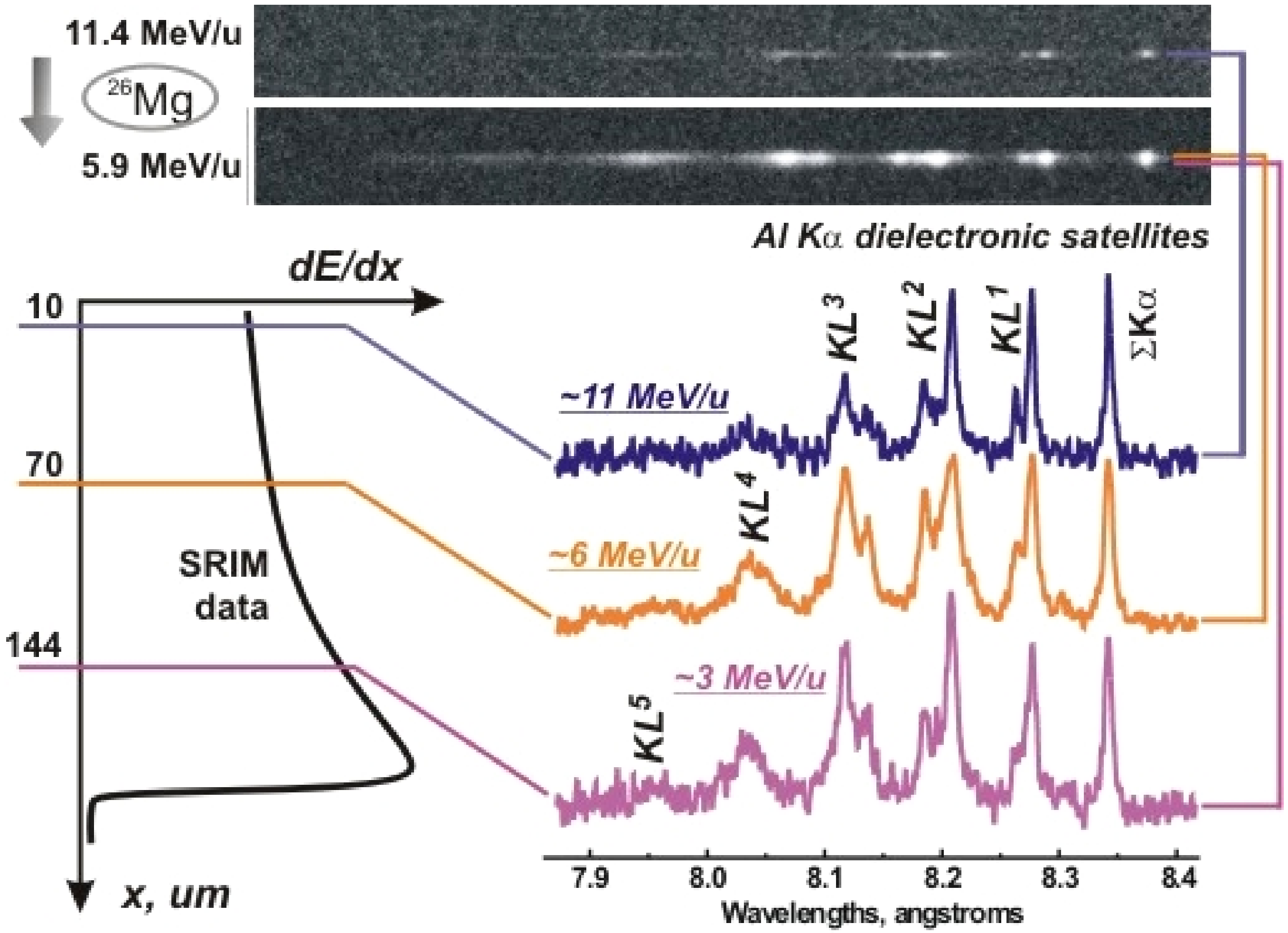




- Increase in specific deposited energy causes the number of L-shell vacancies in target atoms to rise up

Solid aluminum target excitation by Mg ions with different initial energies

(GSI, Darmstadt, Germany)



As the projectile energy comes down and specific energy deposition accordingly grows up the number of L-shell vacancies in target atoms rises up

PLASMA MODEL SUGGESTED

Preassumptions

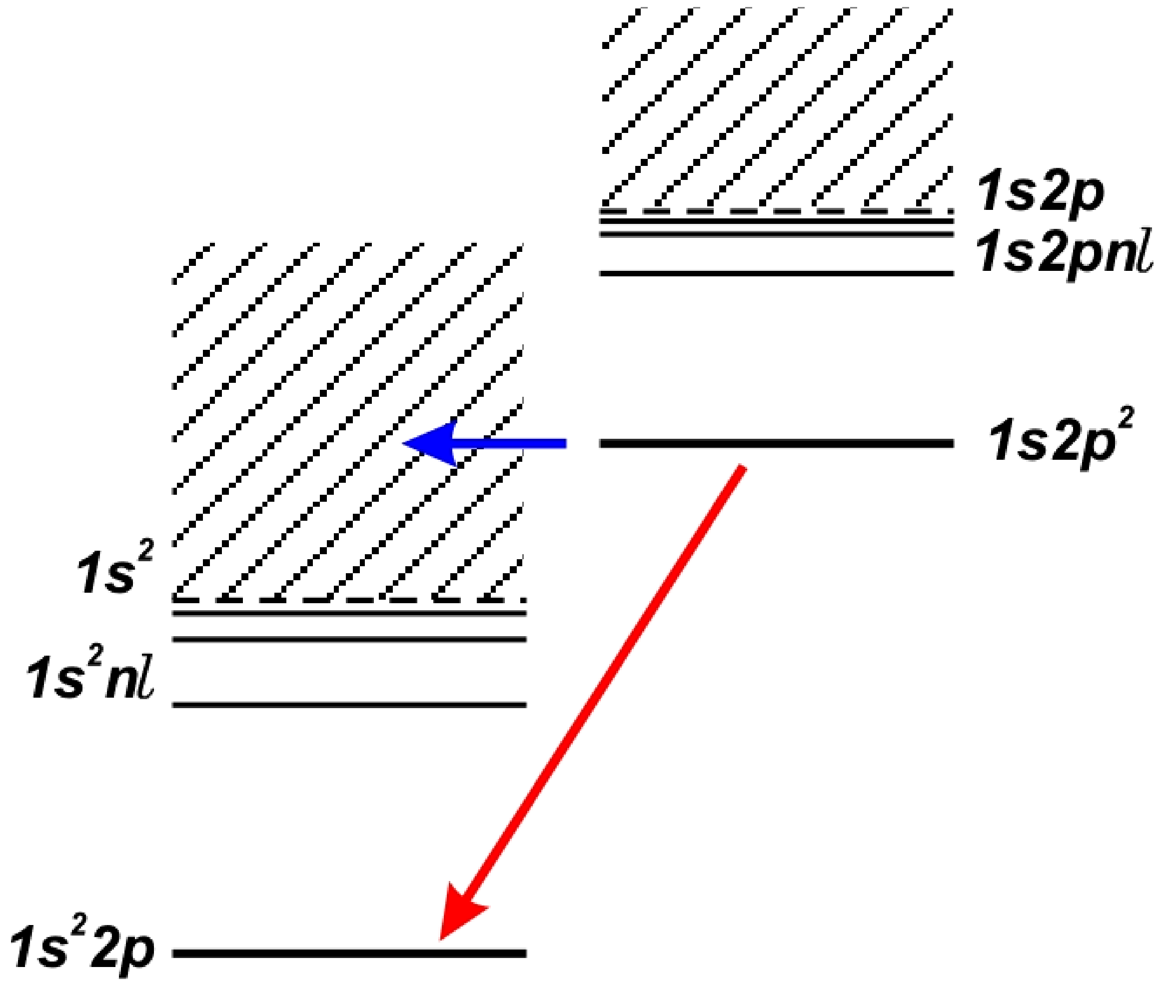
Electron velocity distribution is Maxwellian,

ions keep the initial crystal lattice.

Electron temperature&density are constant,
smearing and recombination are frozen

Kinetics of
excited state populations
and K-vacancy depopulation

Autoionization and Radiative decay

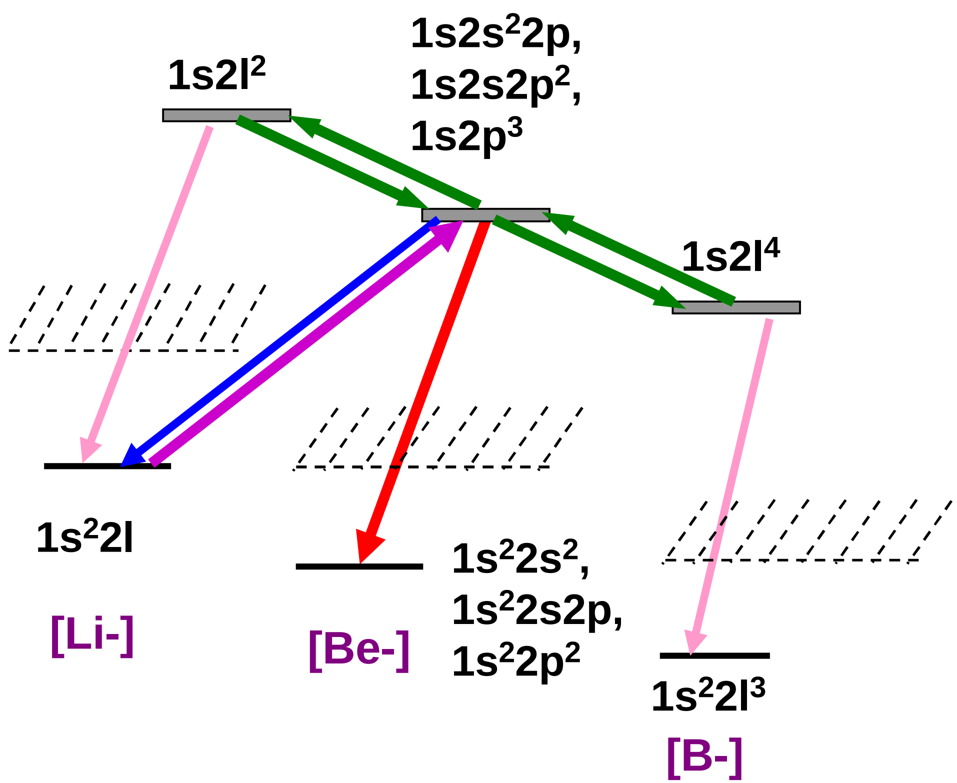


Be-like ion relaxation

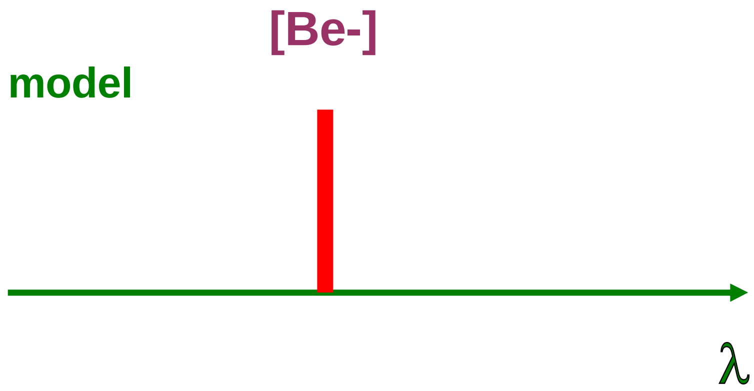
- Autoionization
- Radiative decay
- Dielectronic capture
- 3-body recombination
- Collisional ionization

Autoionization + Radiative decay → "atomic" model

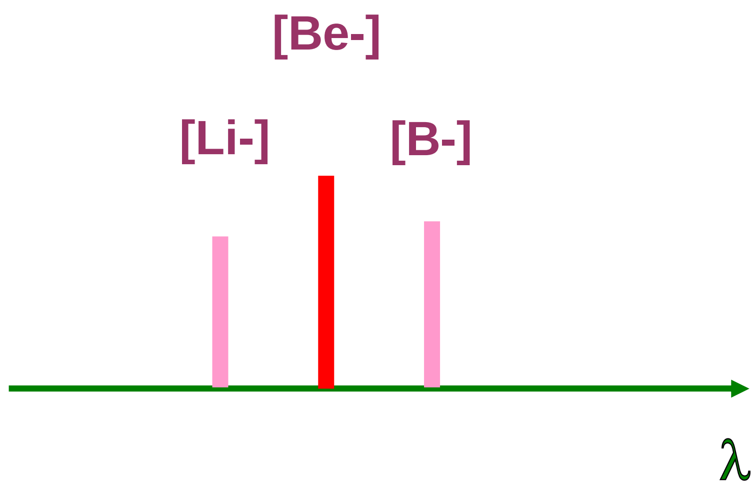
All five processes → "plasma" model



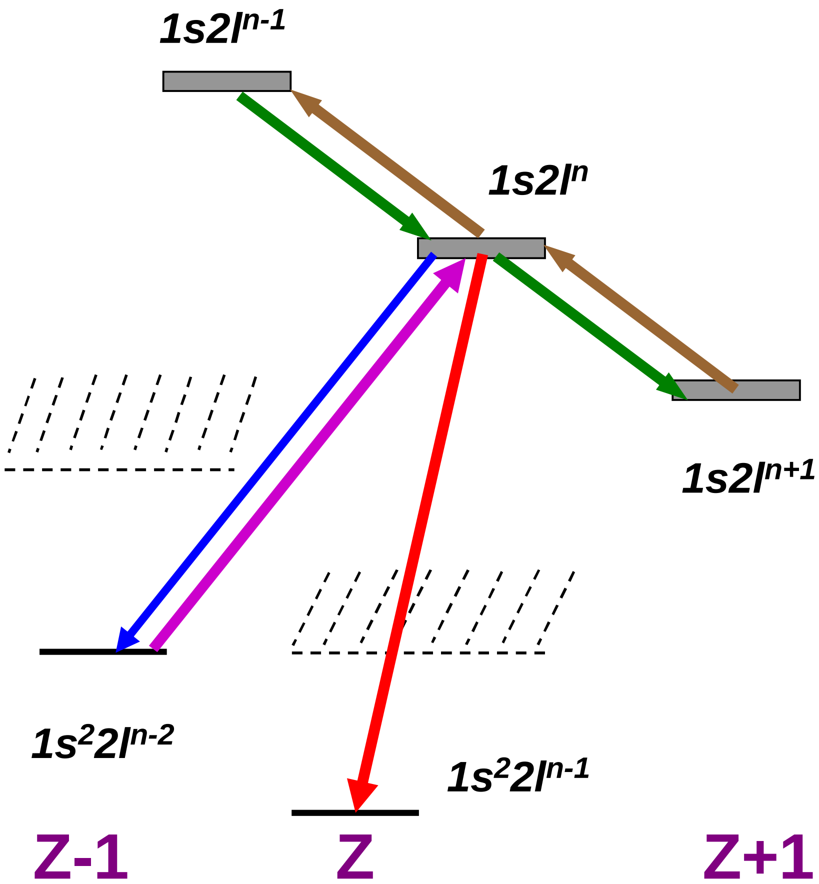
"atomic" model:



"plasma" model:



Kinetic equation for autoionizing state of ion Z



$$\frac{d}{dt}N(1s2l^n) =$$

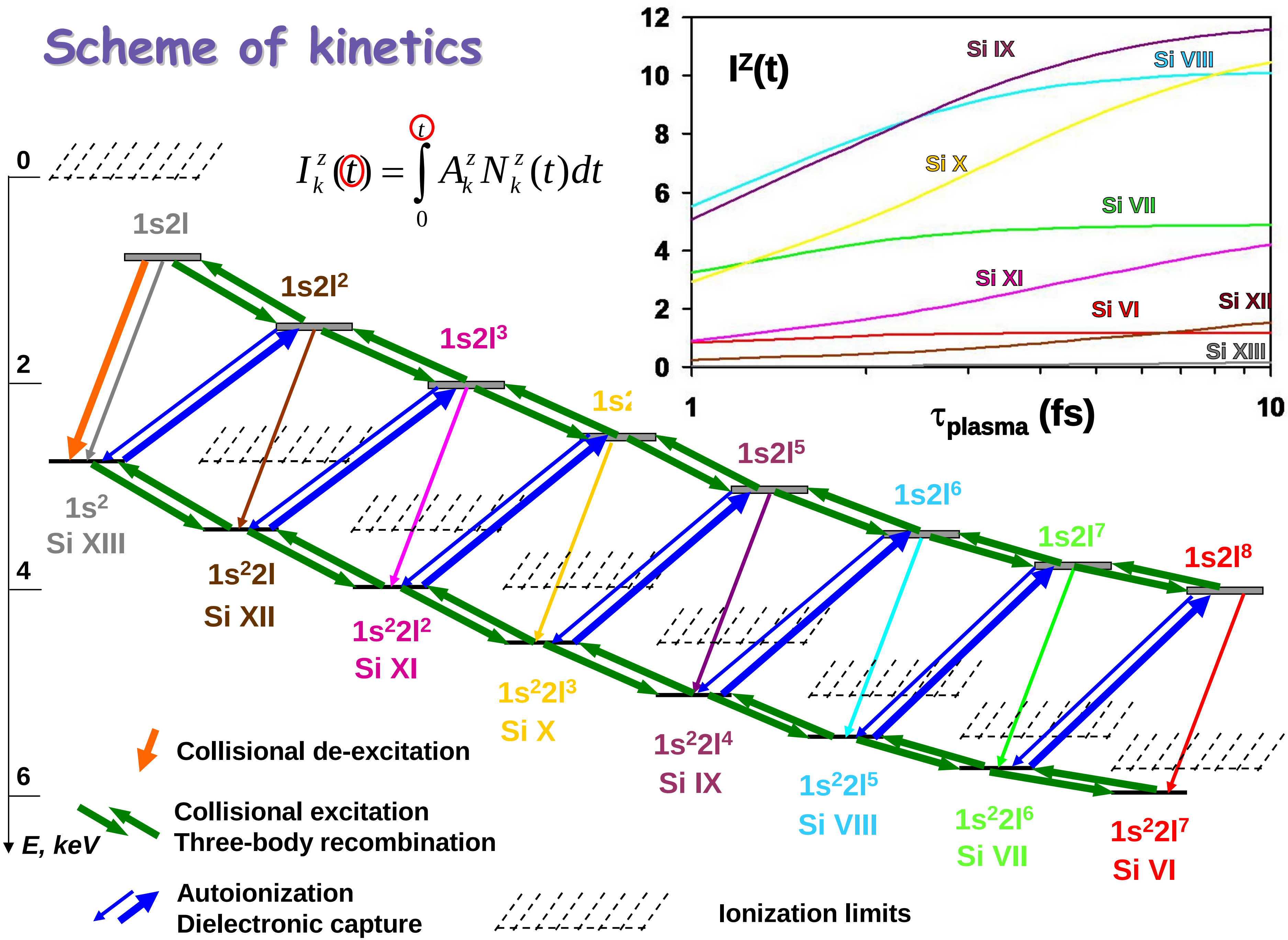
$$- N(1s2l^n)\{A_r(1s2l^n - 1s^2 2l^{n-1})$$
$$+ \Gamma_a(1s2l^n - 1s^2 2l^{n-2})$$
$$+ N_e C_{ion}(1s2l^n - 1s2l^{n-1})$$
$$+ N_e^2 C_{rec}(1s2l^n - 1s2l^{n+1})\}$$
$$+ N(1s2l^{n+1}) N_e C_{ion}(1s2l^{n+1} - 1s2l^n)$$
$$+ N(1s2l^{n-1}) N_e^2 C_{rec}(1s2l^{n-1} - 1s2l^n)$$
$$+ N(1s^2 2l^{n-2}) N_e Q_d(1s^2 2l^{n-2} - 1s2l^n)$$

Autoionization | Dielectronic capture | 3-body recombination

Radiative decay | Collisional ionization

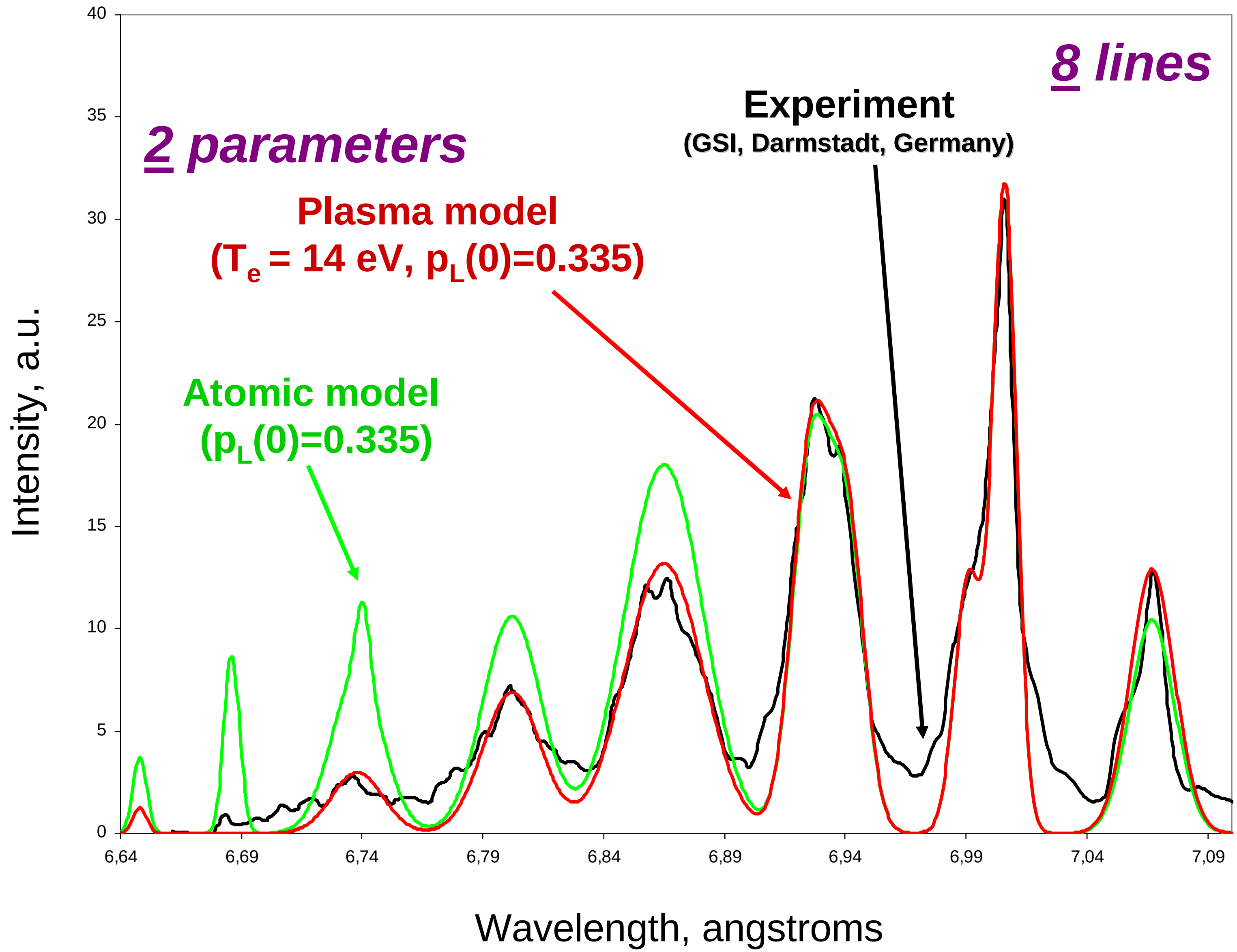
Scheme of kinetics

$$I_k^z(t) = \int_0^t A_k^z N_k^z(t)\,dt$$

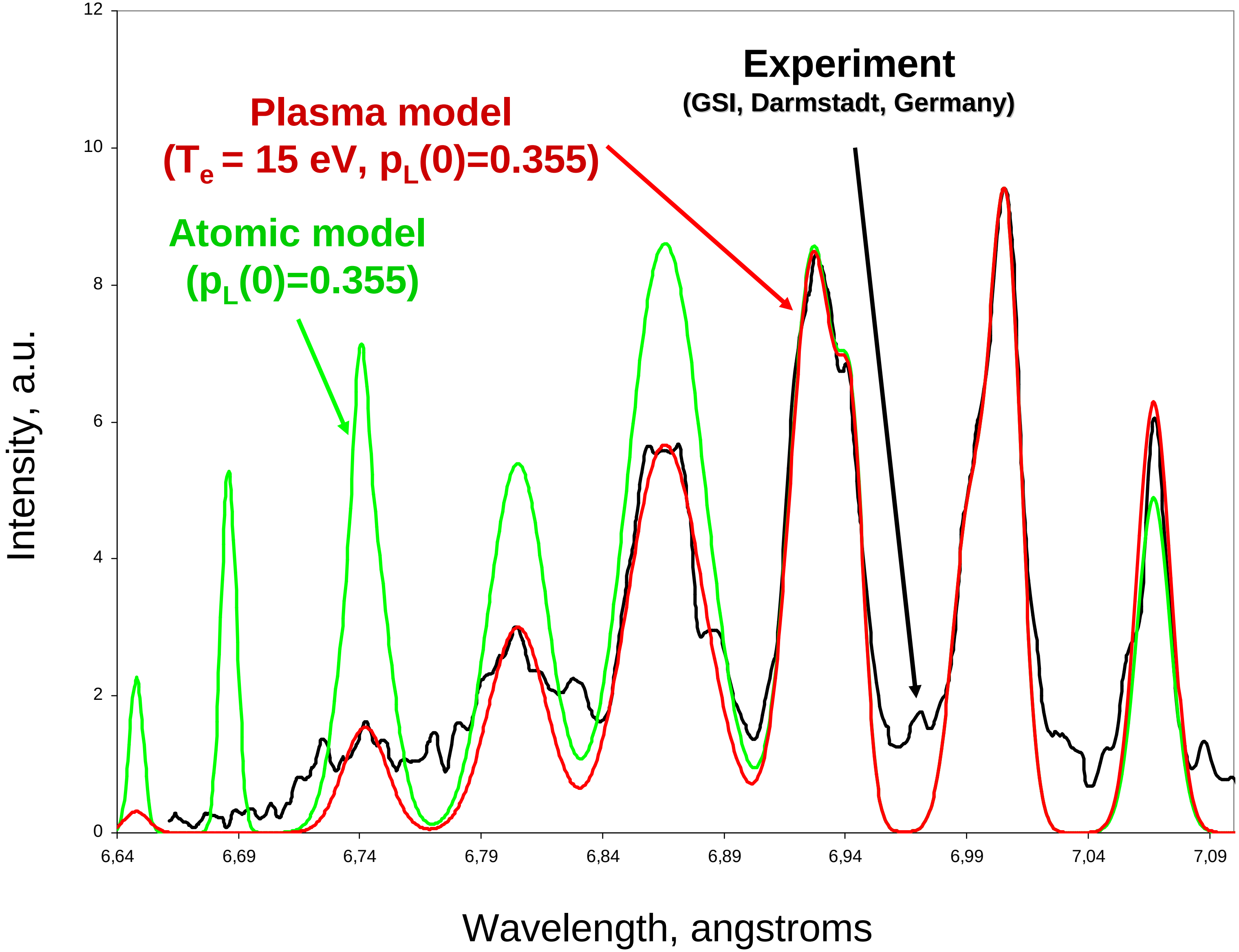


Adjustment of the model to the experimental data

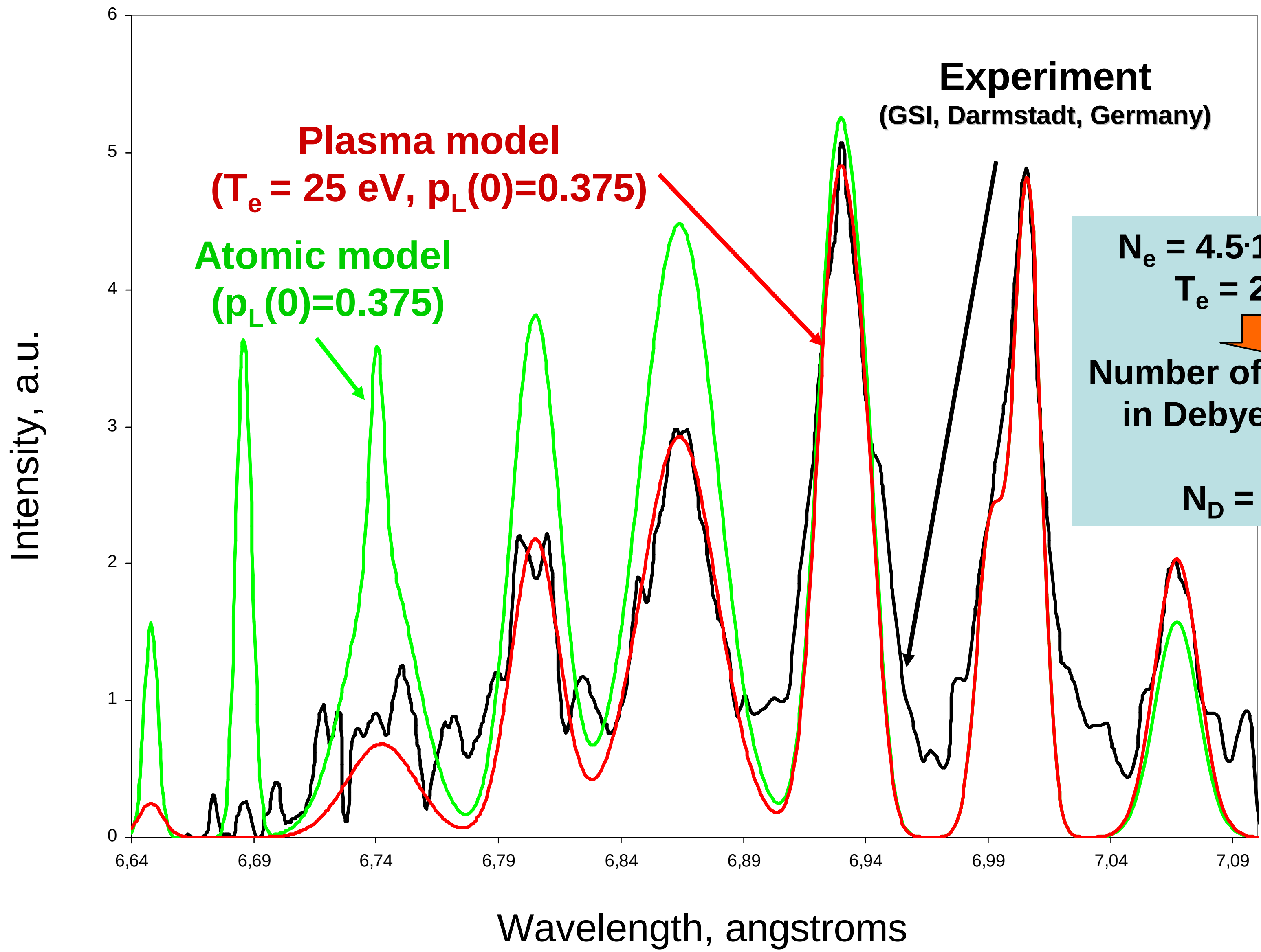
Si ions in SiO_2 aerogel, 100 μm from surface



Si ions in SiO_2 aerogel, 800 µm from surface



Si ions in SiO_2 aerogel, 1200 μm from surface



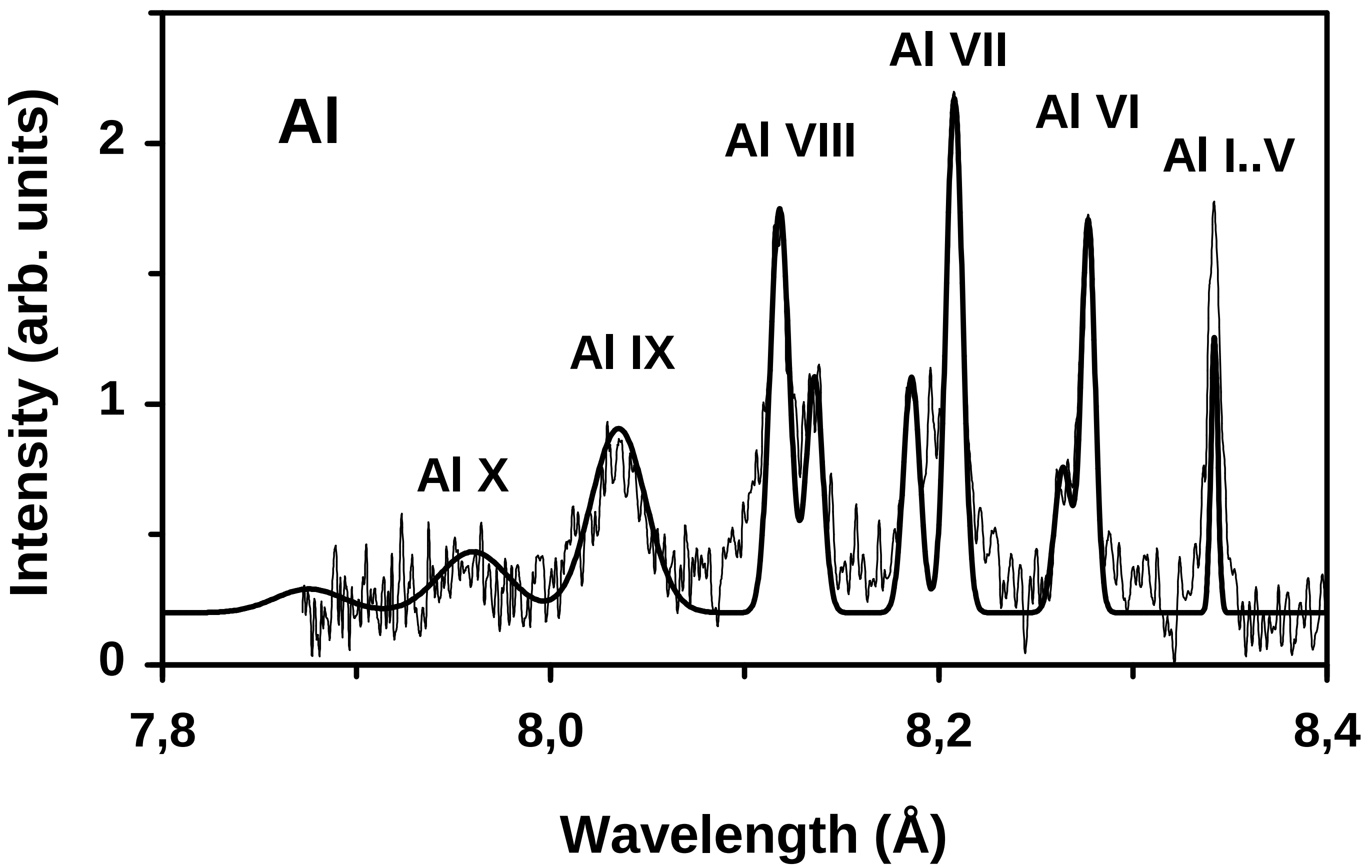
$N_e = 4.5 \cdot 10^{23}$ cm^{-3}
T_e = 25 eV

Number of electrons in Debye sphere:

N_D = 0.35

Comparison with experiments

Projectile: Mg^{+7} Target: solid Al

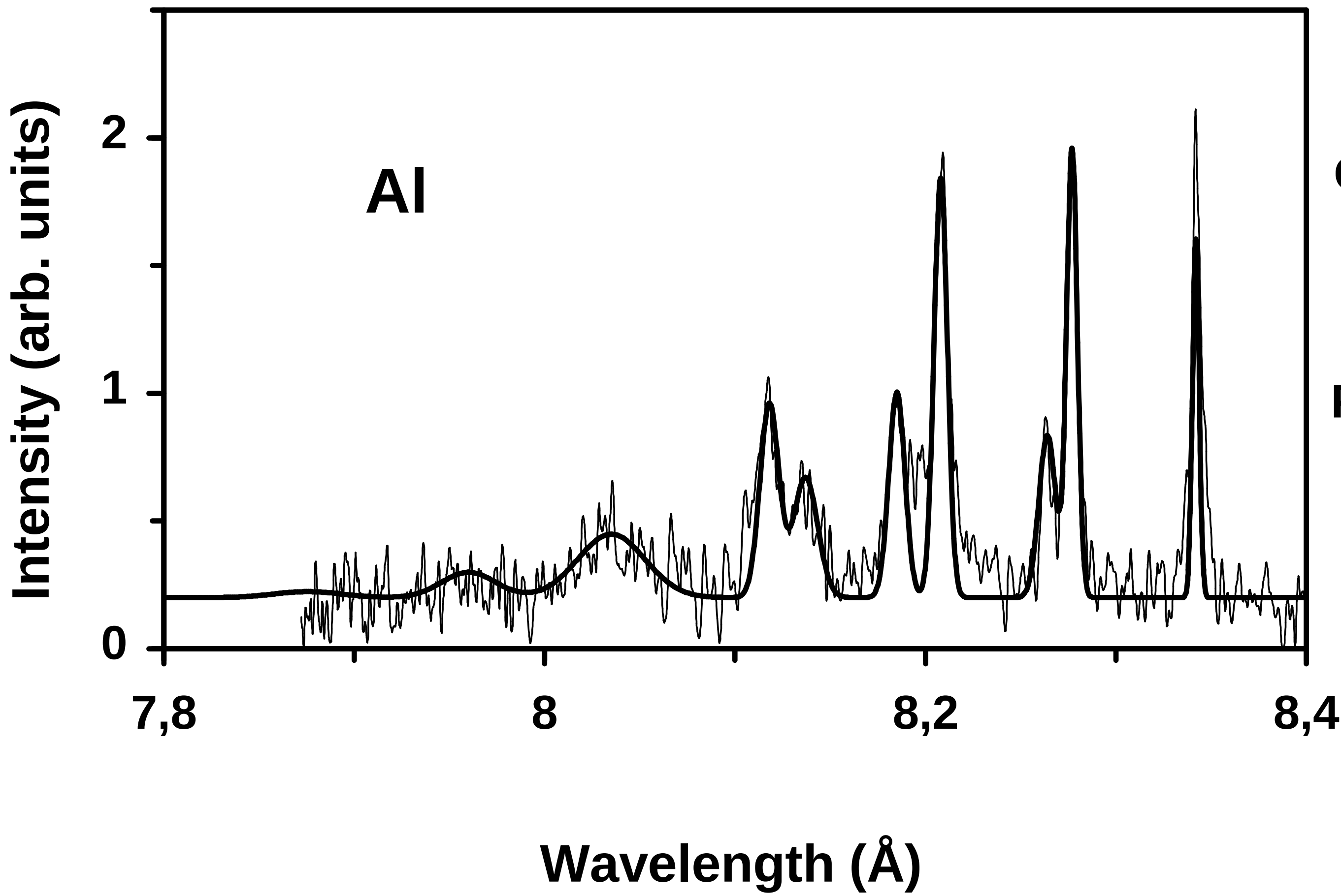


Experiment
GSI, Germany
(thin line)
E ~ 3 MeV/u

Plasma model
(thick line)
T_e = 40 eV
$p_L(0)$ = 0.285

Comparison with experiments

Projectile: Mg^{+7} Target: solid Al



Experiment
GSI, Germany
(thin line)
E ~ 11 MeV/n

Plasma model
(thick line)
T_e = 25 eV
$p_L(0)$ = 0.235

Plasma parameters measured

Ion - Target	Ion Energy MeV/u	Measured values	
		$p_L(0)$	T_e (eV)
Ni^{+14} – SiO_2	11	0,33	14
Ni^{+14} – SiO_2	6	0,335	15
Ni^{+14} – SiO_2	3	0,34	25
Mg^{+7} – Al	11	0,235	25
Mg^{+7} – Al	3	0,285	40

The values considered as initials for MD relaxation modeling:

Free electron density

~ $4*10^{23}$ cm^{-3}

Mean energy of free electrons

~ 10 - 50 eV

SELF CONSISTENCY OF THE PLASMA MODEL DEVELOPED

Molecular dynamics modeling&simulation are used to check the preassumptions

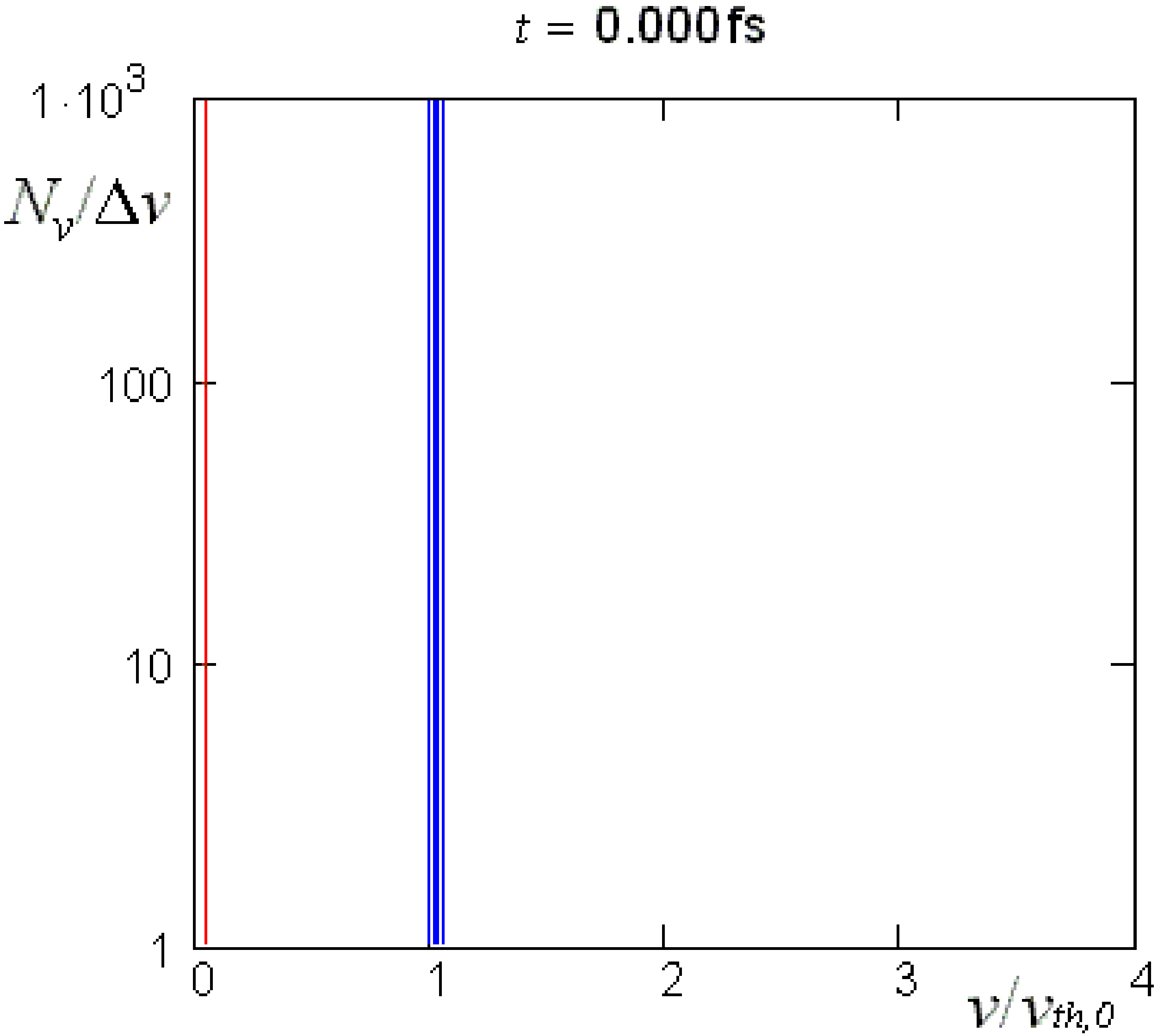
Preassumptions

Electron velocity distribution is Maxwellian,

ions keep the initial crystal lattice.

Electron temperature&density are constant,
smearing, cooling and recombination
are frozen for the period of X-ray emission

Electron velocity distribution



Initial conditions:

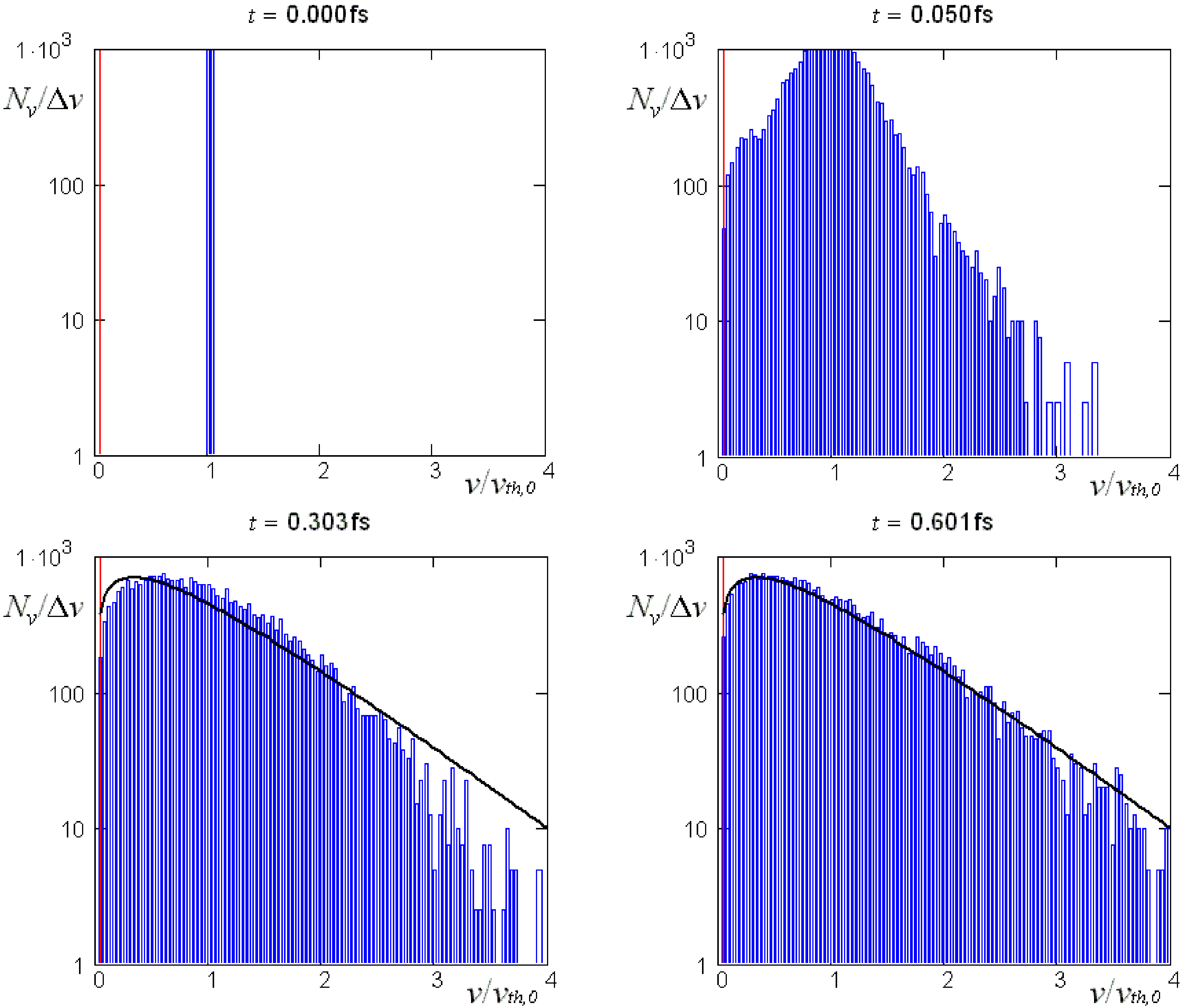
$T_e(0)$ = 55 eV

ions are static

$n_e = 2 \cdot 10^{23} cm^{-3}$

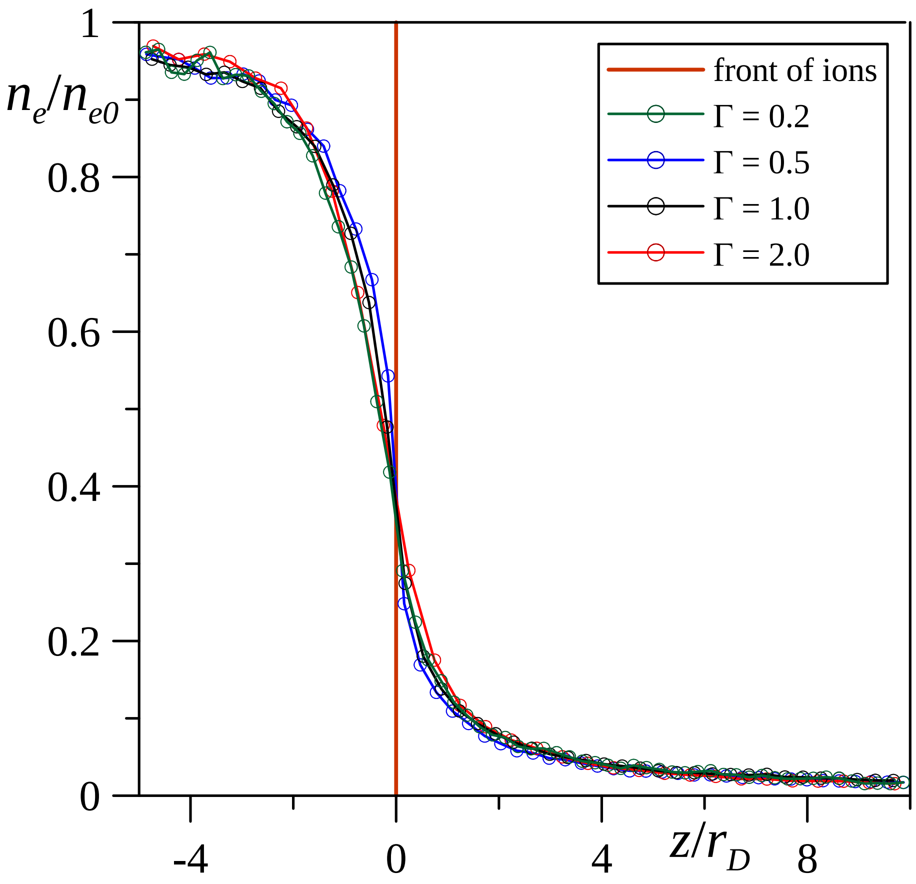
$\Gamma_e = 0.25$

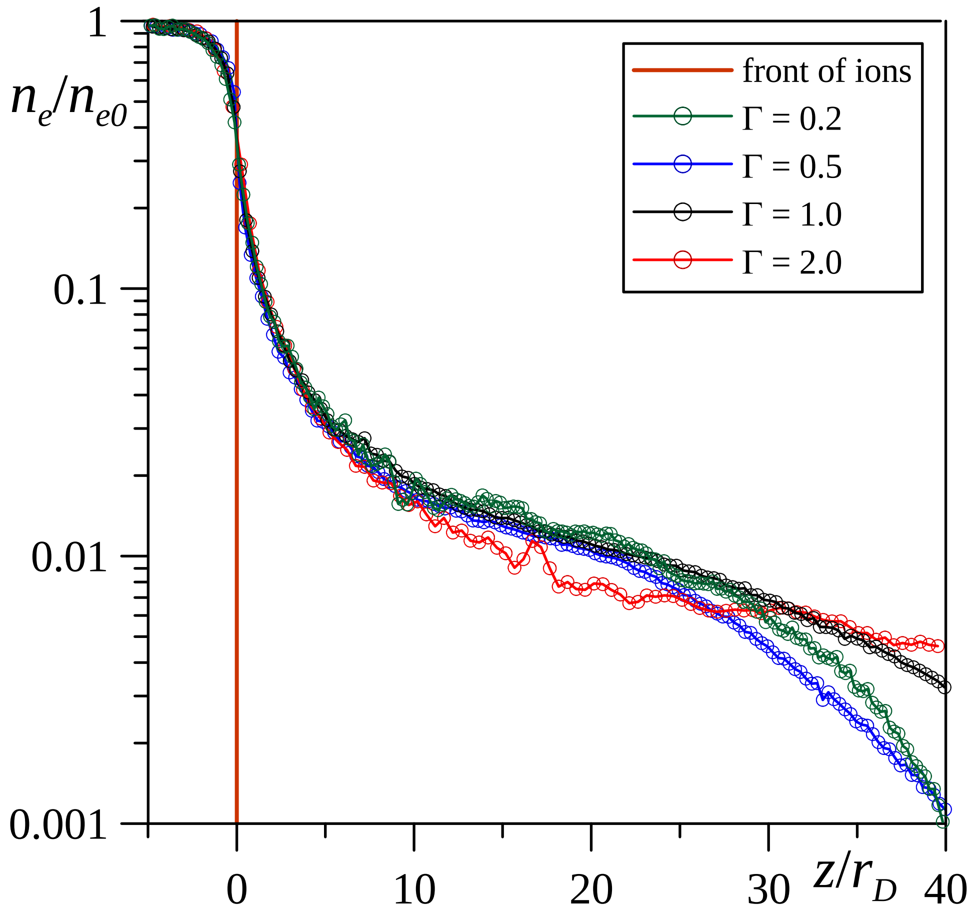
$Z = 2$



t = 0.000fs
t = 0.050fs
t = 0.303fs
t = 0.601fs
1·10^3
100
10
1
N_v/Δv
0
1
2
3
4
v/v_th,0

Electric double layer





Time of establishment 10 – 40 fs

Conclusions

Plasma model is developed for the initial stage of solid media excitation by a single swift heavy ion:

- free electrons with Maxwell velocity distribution
- constant electron temperature of ten's eV
- constant electron density ~ 10^{23} см$^{-3}$
- solid-state ionic lattice is stable, Z = 2 – 7

The values of **two** plasma parameters are adjusted to **eight** line results obtained by the X-ray spectroscopy

Molecular dynamics modeling&simulation are used to validate the ***self consistency*** of the plasma ***parameters adjusted*** and ***preassumptions*** of the plasma model developed over the range of projectile ion energy range available

Similarity of novel forms of WDM generated by fast single ions, XUV laser, exploding wires

solid state density, electrons are heated up to *tens* eV,
cold ions keep original crystallographic positions,
but electron band structure and phonon dispersion are changed
(examples are given in tomorrow's Stegailov's talk),

transient but steady (quasi-stationary for a short time) state of non-equilibrium, uniform plasmas (no reference to non-ideality, both strongly and weakly coupled plasmas can be formed)

spectral line spectra are emitted by ion cores embedded in plasma environment which influences the spectra strongly (another example was given in today's Lankin&Norman's talk),

lifetime limiting processes:
electron-phonon exchange, collisional electron cooling,
recombination (remember suppression in Lankin&Norman's talk).

The main difference between WDM created by X-ray lasers and single fast heavy ion

X-ray laser: two steps heating

$K^2L^8M^n$ + X-ray photon ⇨ $K^2L^7M^n$ + e (photoionization)

$K^2L^7M^n$ ⇨ $K^2L^8M^{n-1}$ + e (Auger recombination)

Fast heavy ion: also two steps

$K^2L^8M^n$ + A^{+q} ⇨ KL^{8-k} + A^{+q} + (k+1+n)e (impact ionization)

KL^{8-k} ⇨ K^2L^{8-k-1} + e (Auger recombination)

(k+1+n) >> 1 second step is not important in this case

Diversity

properties	XUV laser	fast single ions	exploding wires
degree of K-shell ionization	none	small but important for diagnostics	small
degree of L-shell ionization	small	medium	any
Auger decay heating	very important	small contribution	not important
diagnostics	VUV and UV emission	X-ray emission	energy deposition
space configuration	cylindrical flat layer	nanochannel	microcilinder
lifetime	from fs’s up to ns’s	picoseconds	nanosecond?
limiting processes	electron-phonon exchange and spinodal decay		
	inertial dispersion	collisional recombination and cooling	
			surface melting

ACKNOWLEDGMENTS

We appreciate B. Doyle, H. Hjalmarson, J. Aidun (SNL), M. M. Basko (ITEP), B. M. Smirnov, V. S. Vorobyev, and A.Ya. Faenov for prolific discussions and valuable suggestions.

The work was partly supported by:

RFBR under Grant No. 07-08-00738-a,
RAS Presidium Program of Fundamental Research No. 12
Federal Special Program under contract 02.740.11.0236

S.Pikuz acknowledges RF President Grant No.MK-4375.2008.8,
S. Pikuz and I.Morozov acknowledge CRDF BRHE program.
I. Morozov and A.Lankin acknowledge “Dynasty” foundation

Simulations were performed on MIPT-60 cluster.