Departures from local thermodynamic equilibrium in HID lamps

Departures from Local Thermodynamic Equilibrium in HID lamps

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Outline

1) Introduction: Plasma type: High Intensity Discharge lamps

2) (non-) Equilibrium aspects;

3) Polydiagnostics

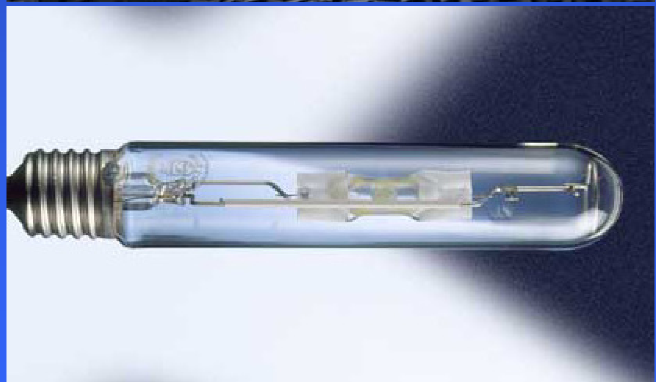
4) Results
Thermal equilibrium T_e versus T_a
Ionisation equilibrium
Time dependence

5) Discussion
General aspects of (non) equilibrium in High pressure Plasmas

Applications of HID lamps I

Applications of HID lamps II


Examples of HID lamps



HID

HID lamps: High Intensity Discharge Lamps

Lighting	Streets, Stadiums, Sport fields
	Car head lights

Mercury; Sodium, Xenon, …Molecules

UHP	200 bar	100 Watt
Metal Halide	10-50 bar	100 Watt
Sulfur lamp	10 bar	1000 Watt

Typical parameters

R < 1 cm

L < 20 cm

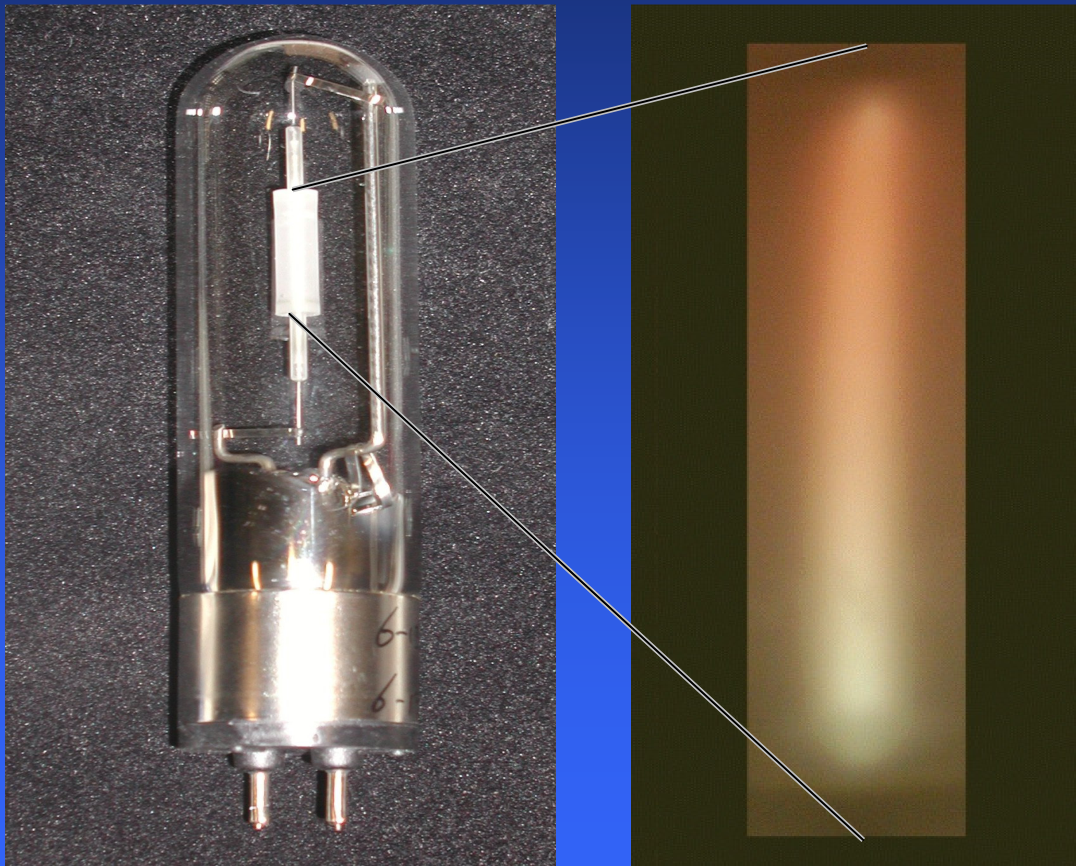
P ~ 100 W

Power density 10^9 W/m^3

$n_e \sim 10^{22}$ m^{-3}

$T_e \sim 6000$ K

The plasma in MH lamps



10 bar Hg

10 mbar addition DyI3

color rendering better

Efficientcy: higher

Color non-uniformity

↑

Segregation

Metal Halide Lamps

COST project 529 Efficient lighting of the 21-th century

Many lamp types; electrons and materials

Low- & high pressure lamps

COST standard lamp	Philips + TUE (Eindhoven)
Arges project	Used in space ISS April 2004 !!
Special interest	Competition convection <-> diffusion

Example of the COST lamp

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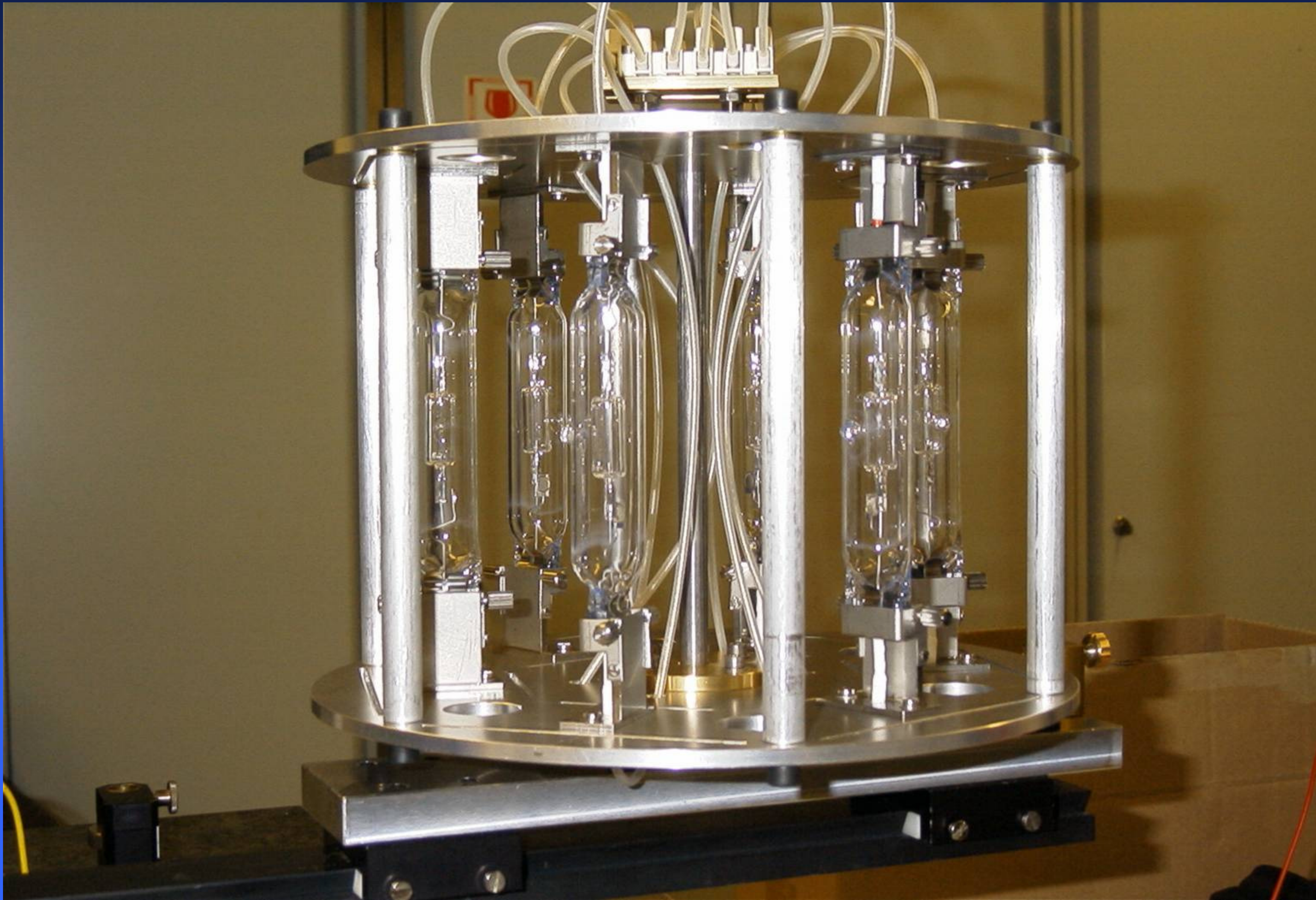
Productivity

Xiaoyan Zhu 2005

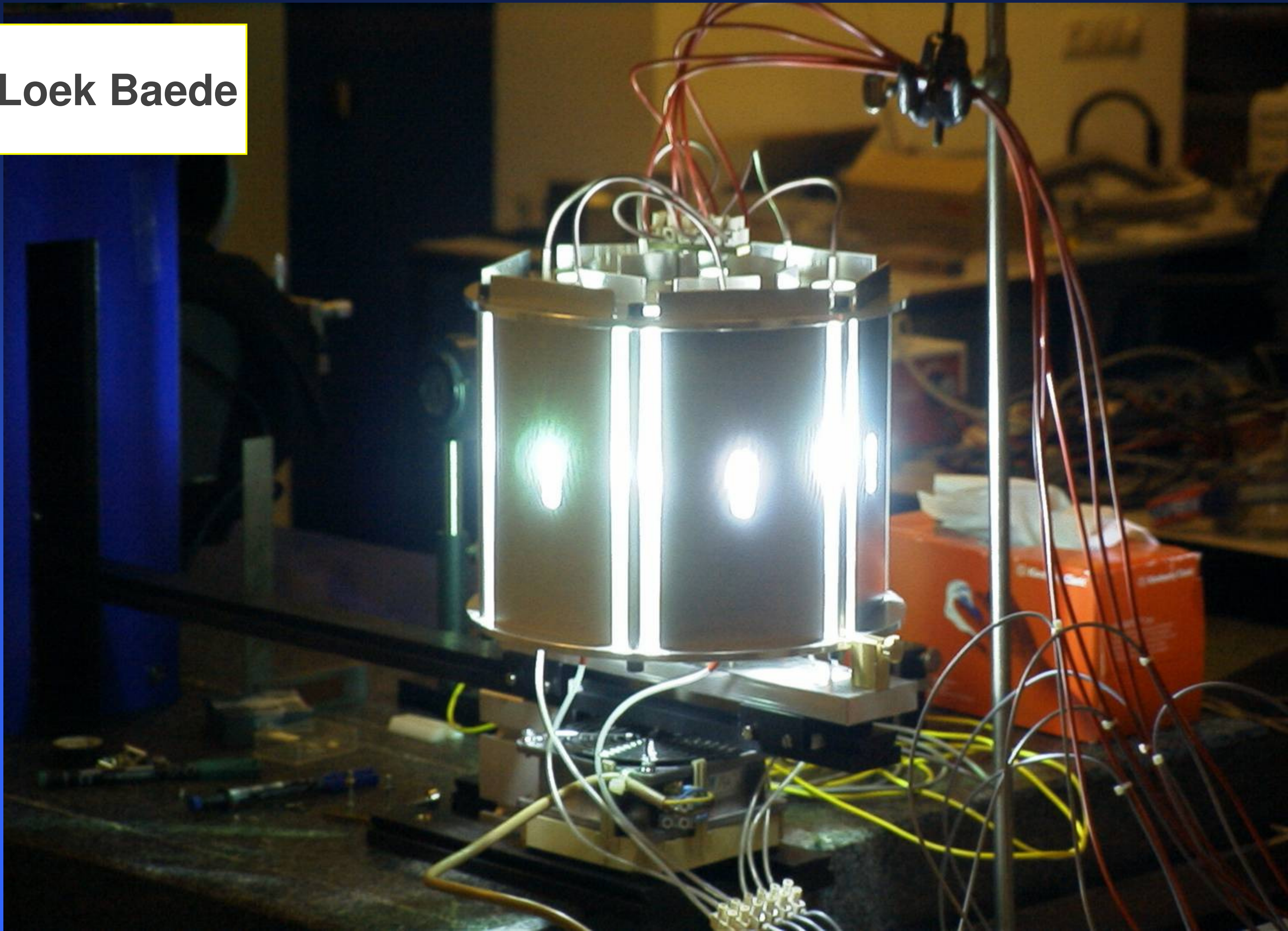
Tanya Nimalasuriya

Mark Beks

Arjan Flikweert



Loek Baede



Zero g: methods limited

TUE (EPG)	TUE (GTD and BLN)	Philips (CDL)
Gerrit Kroesen, Mark Bax, Danny van den Akker, Guido Schiffelers, Pim Kemps, Frank van den Hout, Marc van Kemenade, Job Beckers, Arjan Flikweert, Tanya Nimalasuriya, Winfred Stoffels, Joost van der Mullen, Xiao-Yan Zhu, Charlotte Groothuis, Anette Sezin, Rina Boom, Johan Meulensteen	Peer Brinkgreve, Erwin Dekkers, Jovita Moerel, Rob de Kluijver, Hans Wijtvliet, Ruud de Regt, Fred van Nijmweegen, Roel Smeets, Gerard Harkema, Klaas Kopinga, Paul Beijer, Meindert Janszen, N.N.1, N.N.2, … , N.N. 15	Marco Haverlag, Rob Keijser, Jos Eijsermans, Jacques Claassens, Paul Huijbregts, Wally Dekkers, Jacques Heuts, Jan Peeraer, John Etman, Joop Geijtenbeek, Folke Nörtemann, Cees Reynhout, Bruno Smets, Hans Wernars

Astronaut: André Kuipers (ESA)

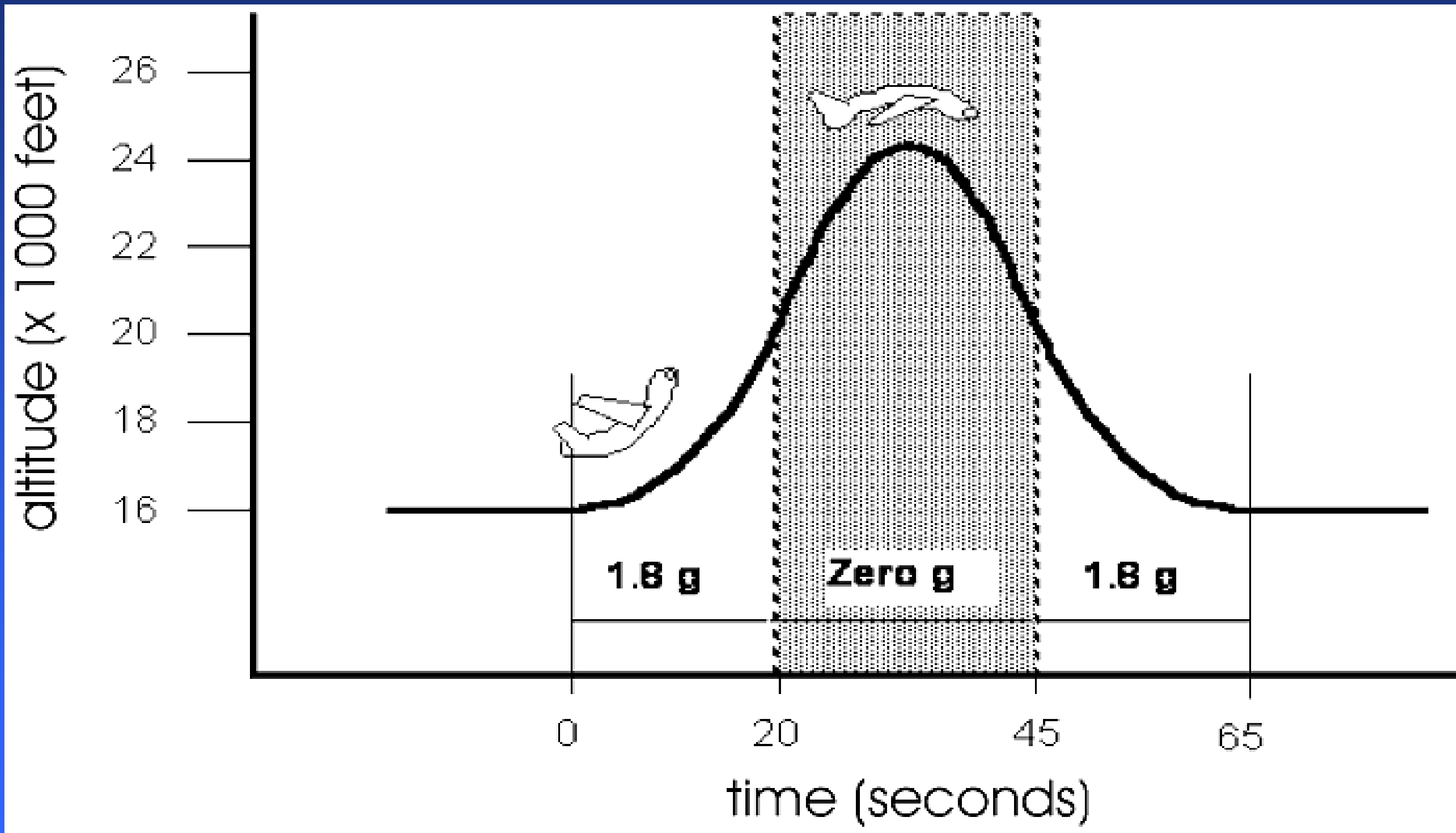
External consultants

Dutch Space: Ron Huijser, Jan Doornink, Geert Brouwer, Fons van Wijk, King Lam, Luc van den Bergh

Kayser-Threde: Roland Seurig, Andreas Kellig

Verhaert: Piet Rosiers Bradford: Gerard Maas

Parabolic Flights



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D092T12-16-47
1 g

Equilibrium concept

LTE: Local Thermal Equilibrium

or better ?

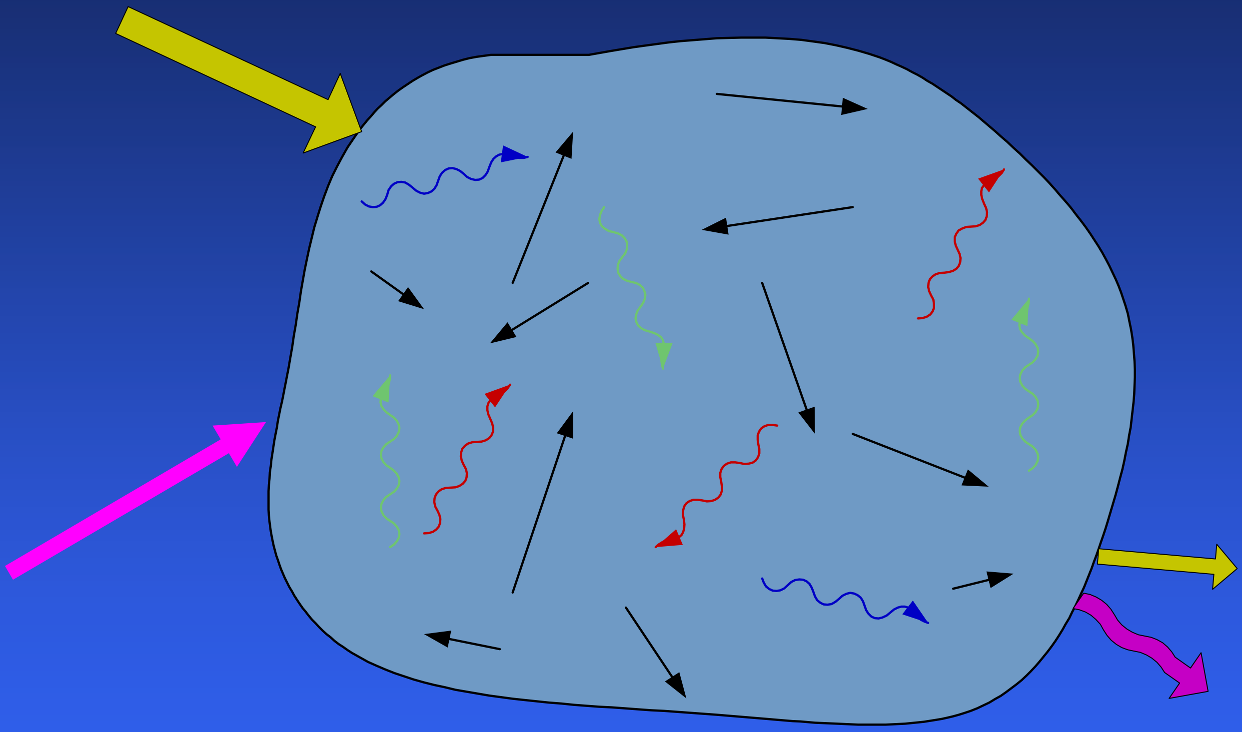
LTE: Local ThermoDynamics Equilibrium

or

LTCE: Local Thermal and Chemical Equilibrium

T_i ?=? T_j

Plasma Artist Impression



Input and Output Intermediated by Vivid Internal Activity

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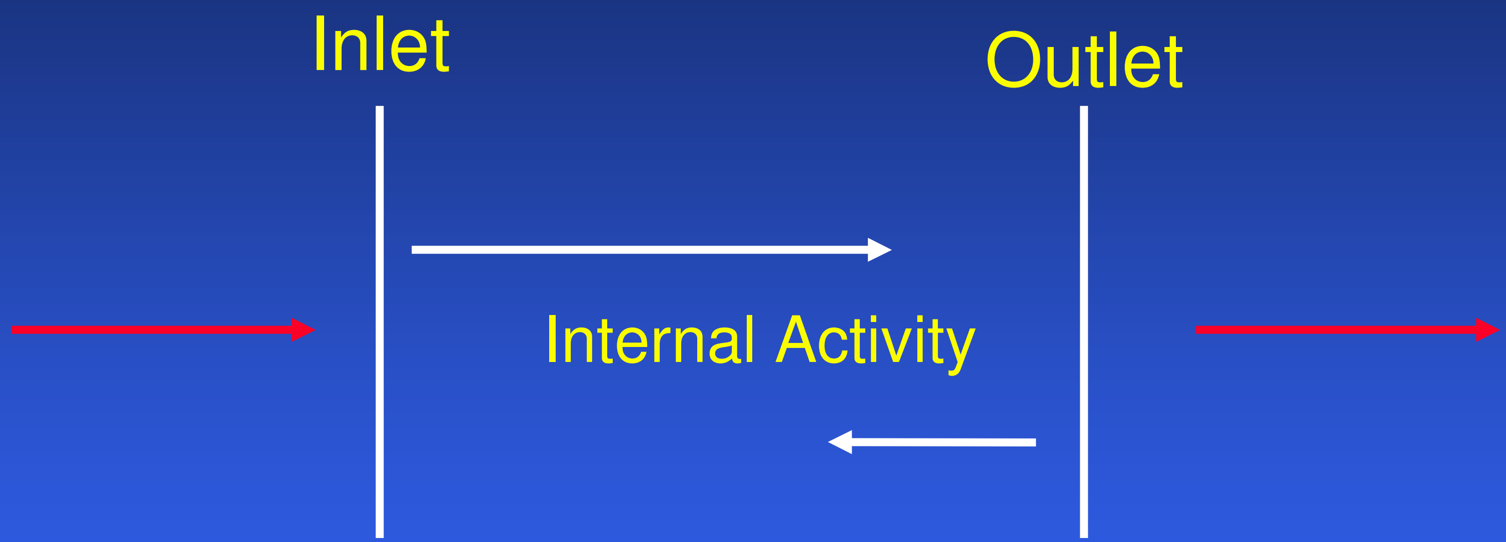
Global Structure

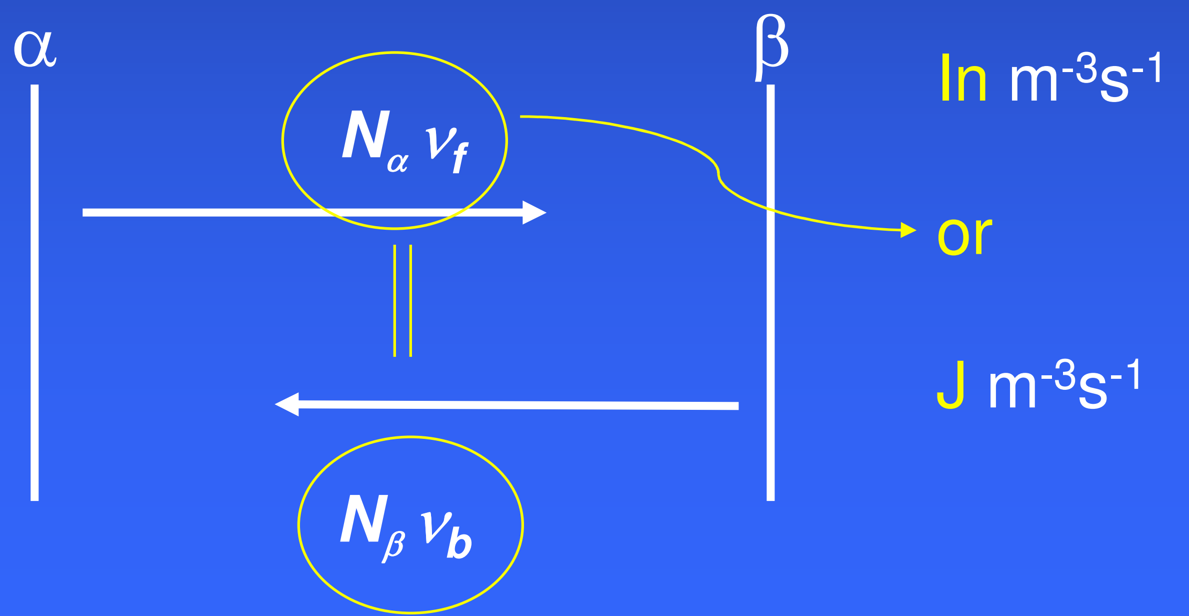


The In/Efflux couple will disturb internal Equilibrium

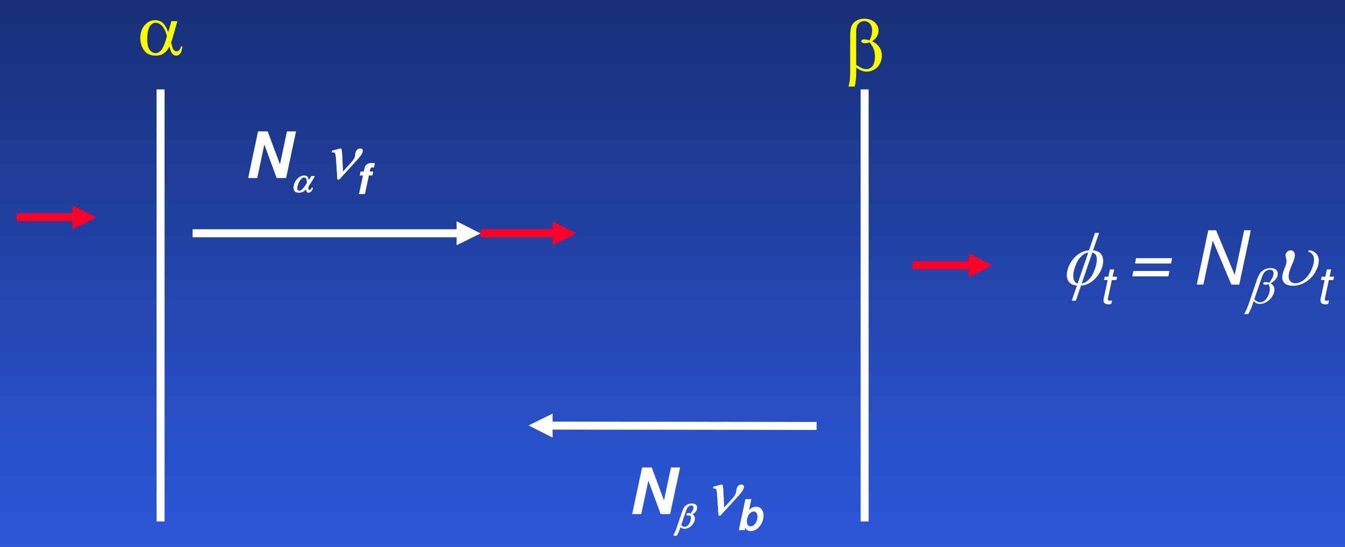
Thermodynamic Equilibrium:
Collection of Bilateral Relations

TE Equilibrium in (violet) thermal dynamics

DB Equilibrium on any **level**
for any process-couple along the same route



Disturbance of BR by an Efflux



Equilibrium Condition: $\upsilon_t/\upsilon_b \ll 1$ or $\upsilon_t \tau_b \ll 1$

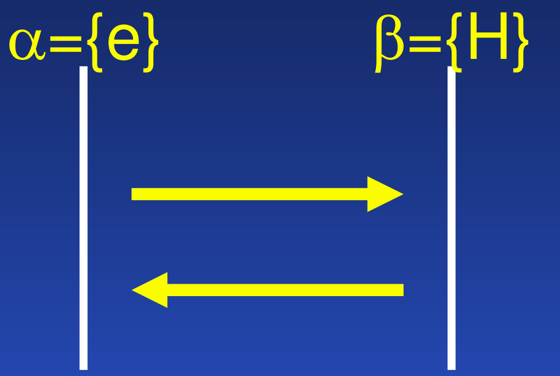
The escape per balance time must be small

EEK

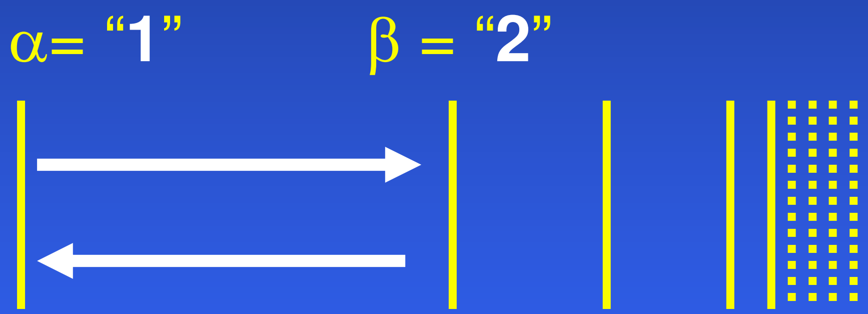
Are electrons the primary agents ??!!

EEK electron excitation kinetics dominant !?

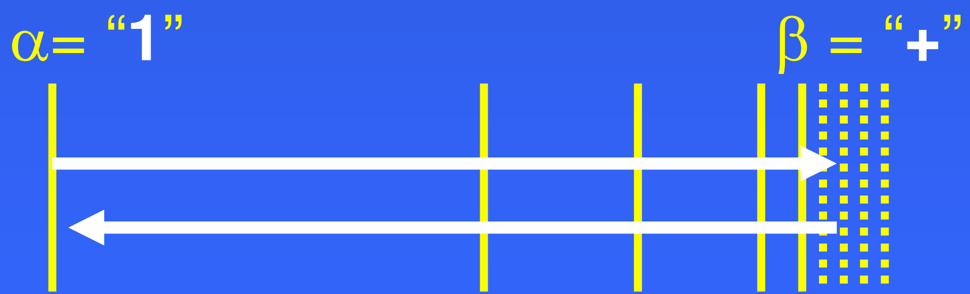
Underlying PROPER Balances



Kinetic Energy Transfer
Maxwell
$T_e = T_h$



Excitation = Deexcitation
Boltzmann



Ionization = Recombin
Saha

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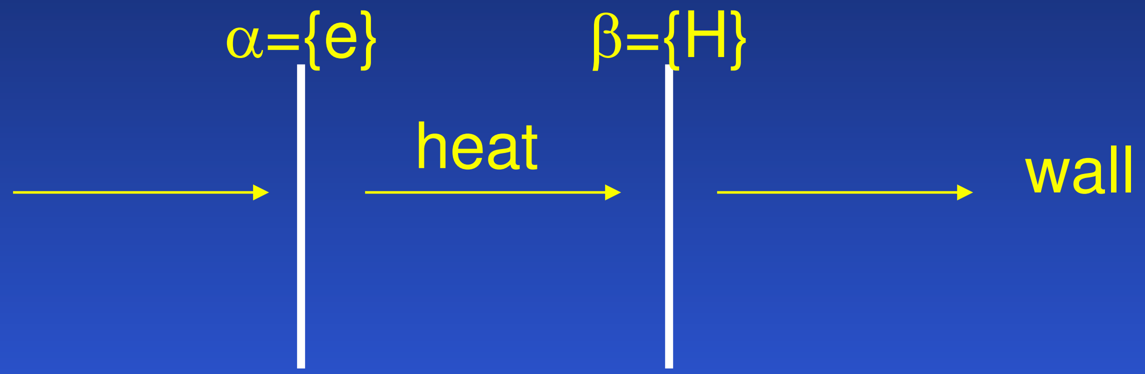
Equilibrium Disturbance



$$n_e n_1 S_{heat}(kT_e \;-\; kT_h) = \lambda/R^2\, T_h$$

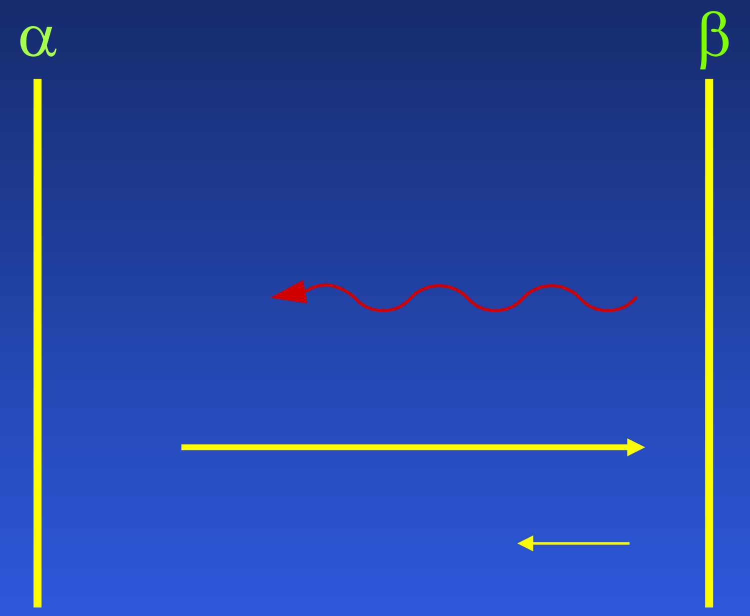
$$\nu_t\ \tau_b = \lambda/(R^2\, n_e n_1 k\, S_{heat})^{-1} \qquad << 1$$

large

huge

$T_e = T_h$?

Radiation escape Griem's criterion



Escape of Photons

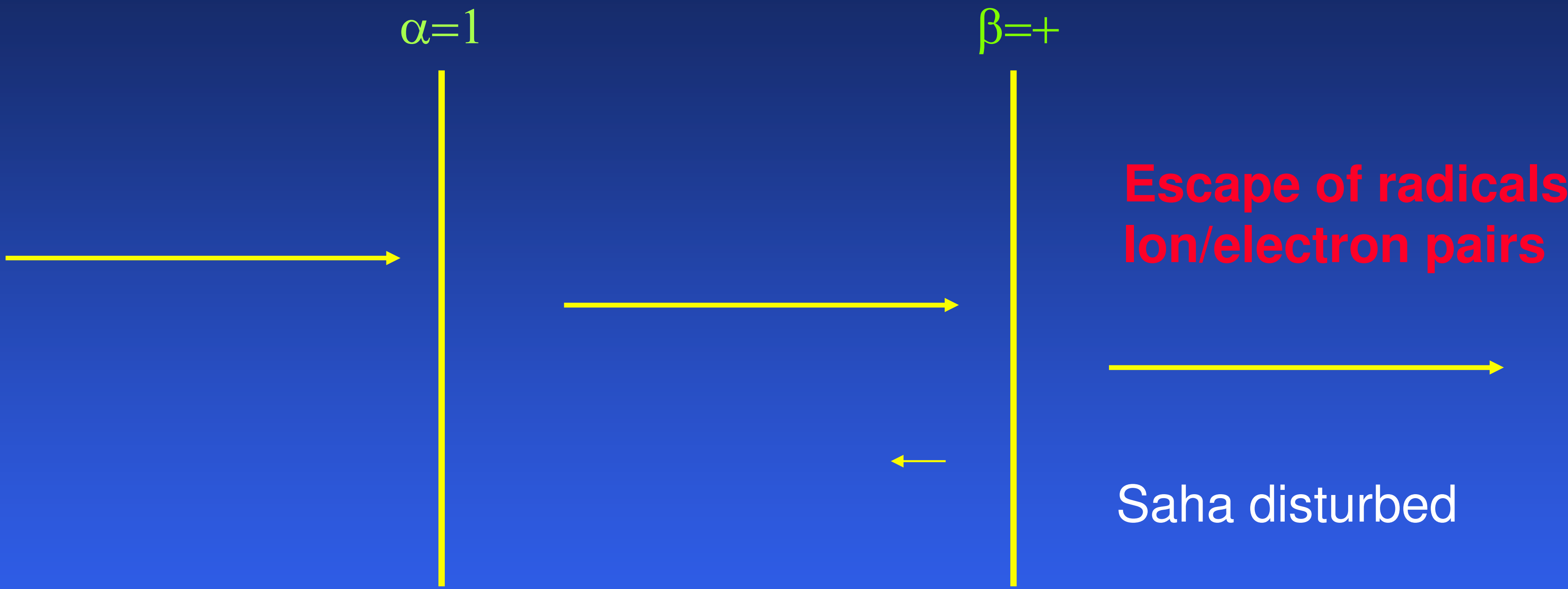
Distrurbed Boltzmann Proper balance

$$y(\alpha) = y(\beta)[1 + (\upsilon_t \tau_b)^B] \quad \textbf{with} \quad (\upsilon_t \tau_b)^B = A/n_e K(2,1)$$

Large **n_e**: small departure

Boltzmann present

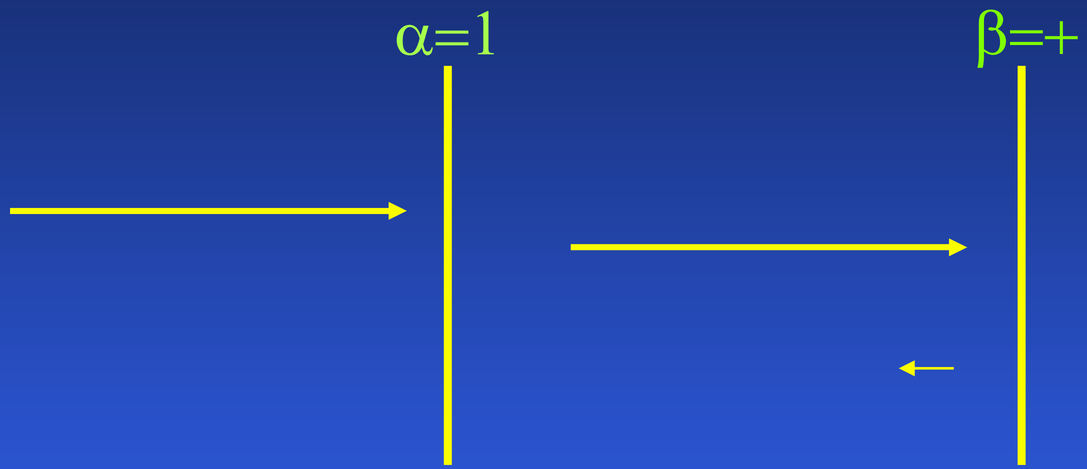
Distortion of Saha



$$y(1) = y(+)\,(1 + \nu_t \tau_b) \qquad \text{or} \qquad \delta b(1) \equiv b(1) - 1 = (\nu_t \tau_b)^S$$

$$y(1)/y(+) \equiv b(1)$$

If Ambipolar Diffusion Dominates



$\phi_t = n_+ \nu_t = \nabla . n_+ \, w_+$

$n_+ \, w_+ = -D_a \, \nabla . n$ **Diffusion**

$\nu_t = D_a / R^2$

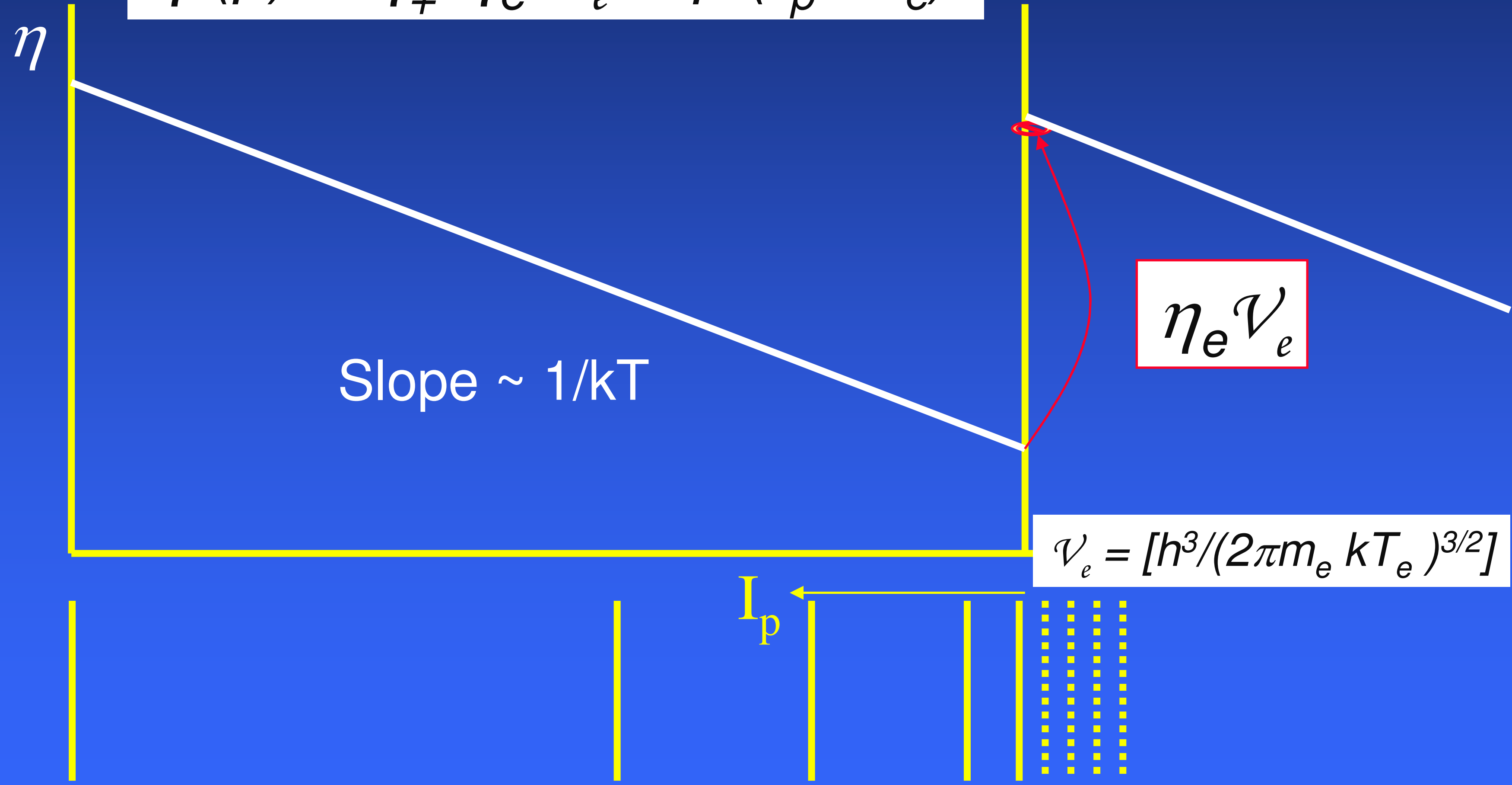
$\delta b(1) = (\nu_t / \nu_b)^s = \nu_t / (n^s(1) \, S_{ion}) \approx C_b \, (A) \times 10^8 \, D_a \, (n_e R)^{-2}$

Large n_e, very small D_a

Saha established !?

General Structure ASDF in full LSE

$$\eta^s(p) = \eta_+ \, \eta_e \, \mathcal{V}_e \, exp \, (I_p/kT_e)$$

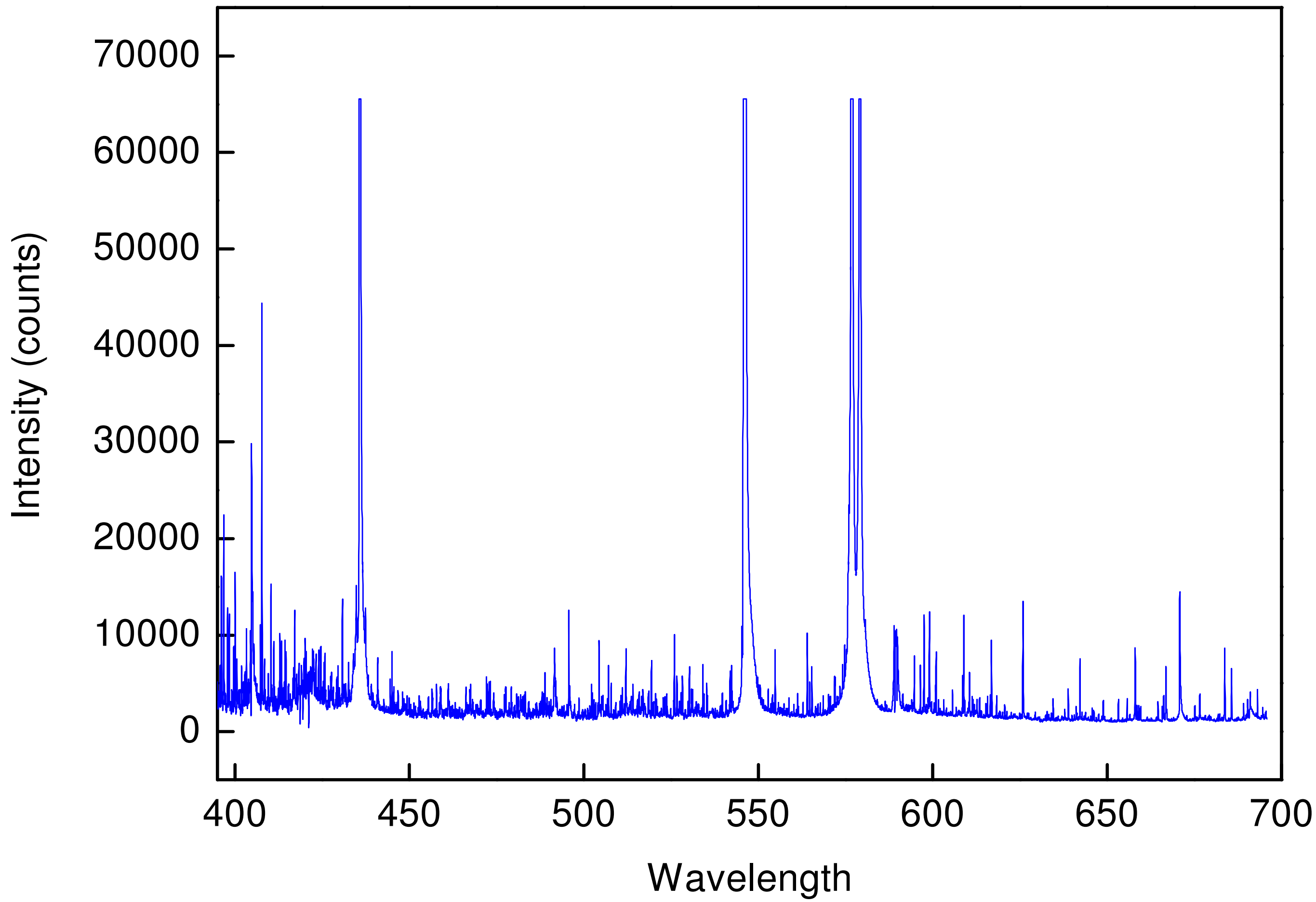


Polydiagnostics

Passive	Absolute Line Intensity
Active	Thomson scattering Xray absorption Xray fluorescencence

Spectral Impression: grass field

Line identification: not trivial

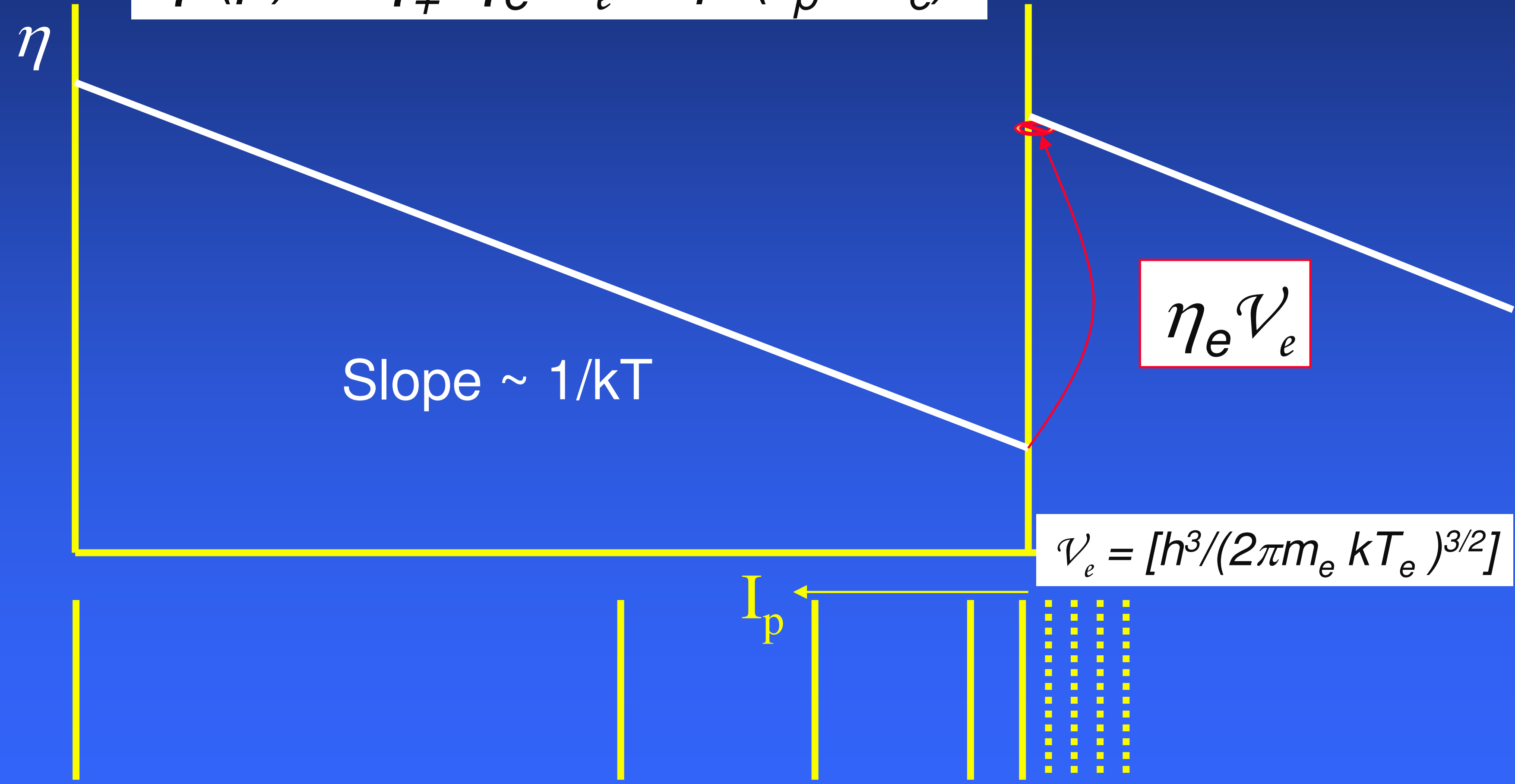


Results Construction ASDF

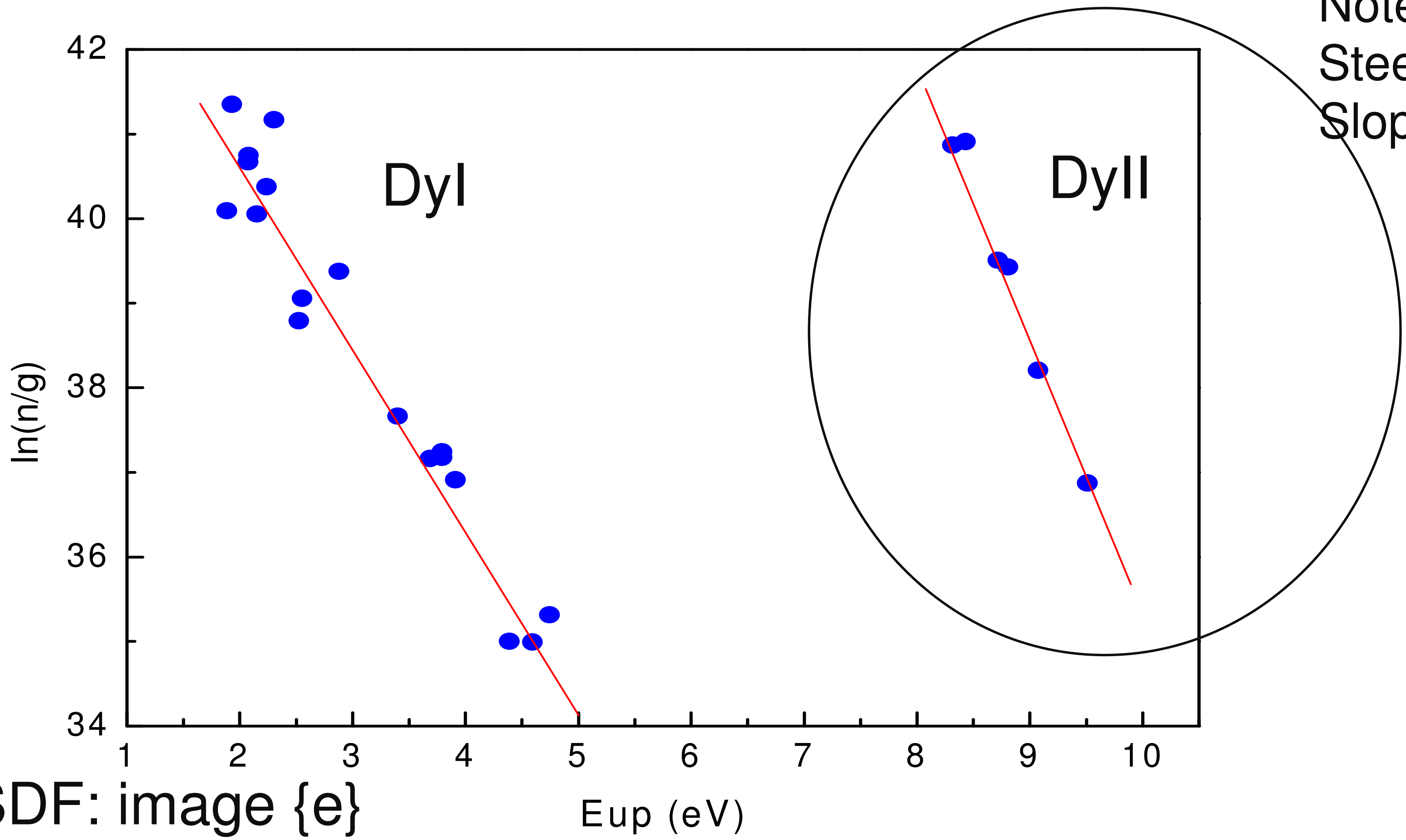
ASDF constructed in	Hg Dy I DyII
Plasma parameters	Slopes give T Saha jump n_e
Results	in general agreement with other methods
However	deviations in slope Dy II for low n_e situations

General Structure ASDF in full LSE

$$\eta^s(p) = \eta_+ \, \eta_e \, \mathcal{V}_e \exp\left(I_p/kT_e\right)$$



ASDF in Dysprosium



Note Steeper Slope

ASDF: image {e} but blurred

T=5524 K

$$\frac{n_{ground}}{g_{ground}} = 3\cdot 10^{19} m^{-3}$$

The infuence of charge number Z ?

$y(\alpha) = y(\beta)[1 + (\upsilon_t \tau_b)^B]$ **with** $(\upsilon_t \tau_b)^B = A/n_e K(2,1)$

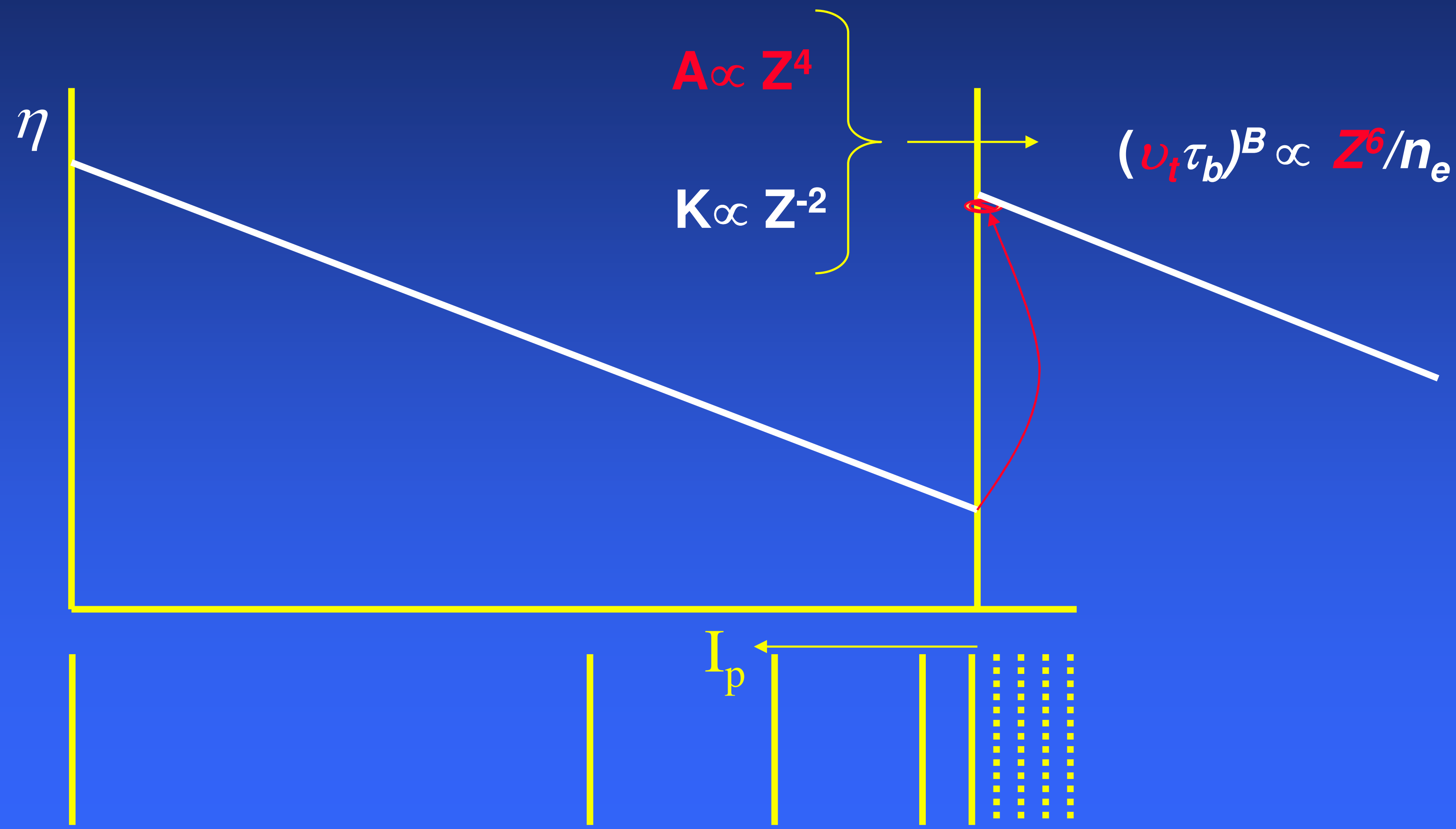
$A \propto Z^4$

$K \propto Z^{-2}$

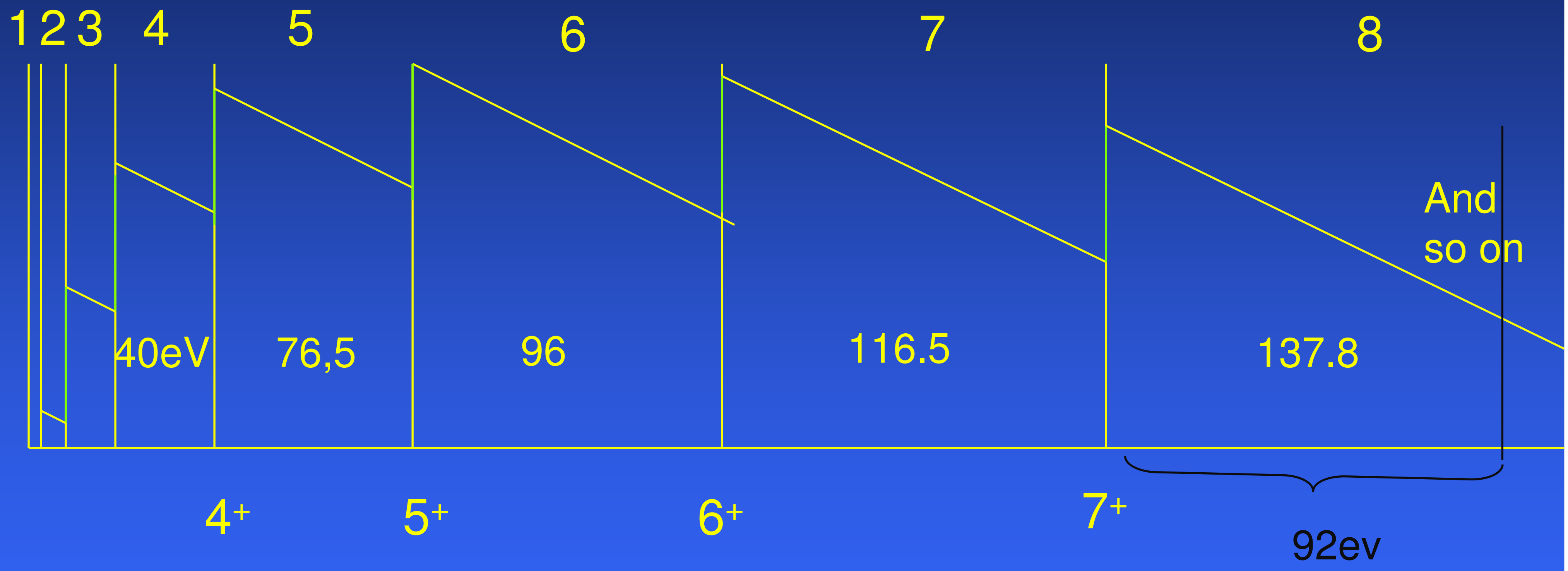
$\longrightarrow (\upsilon_t \tau_b)^B \propto Z^6/n_e$

Increasing Z → increase importance radiative escape!!

General Structure ASDF in full LSE



Comparison with EUV plasmas in Sn
wanted 92eV radiation



$$= \; (n_e/2)\,[h^3/(2\pi m_e k T_e)^{3/2}]$$

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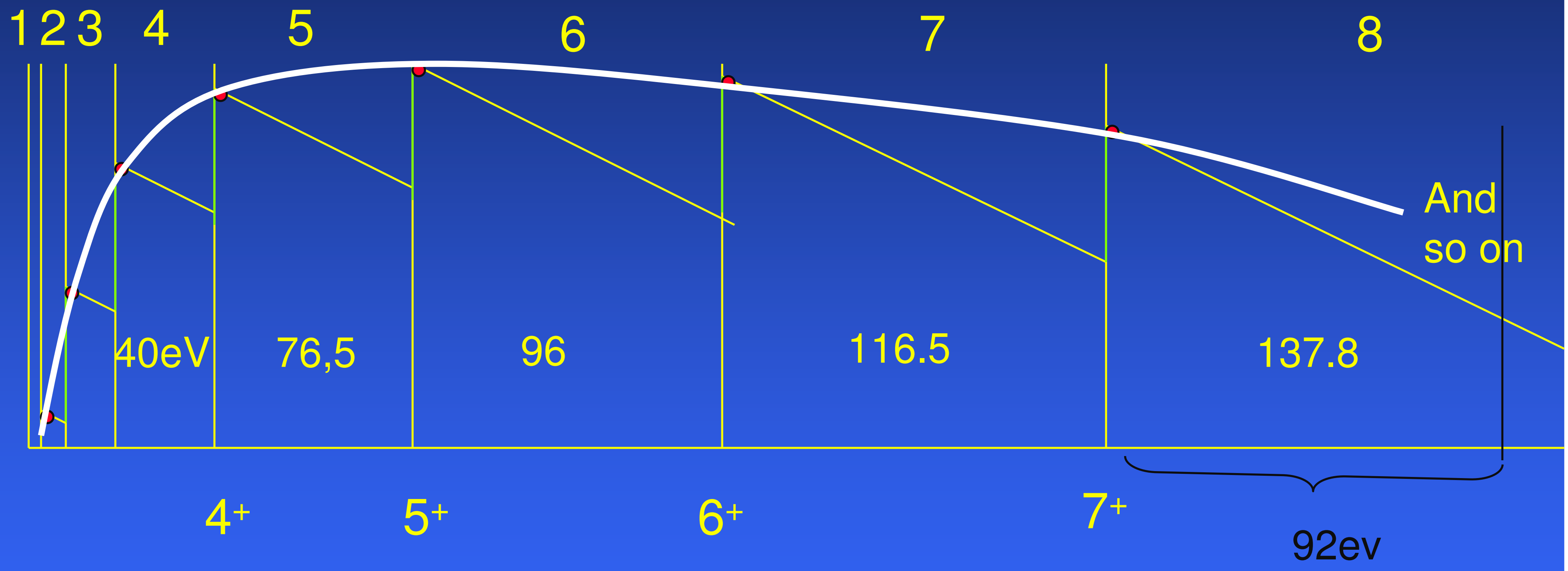
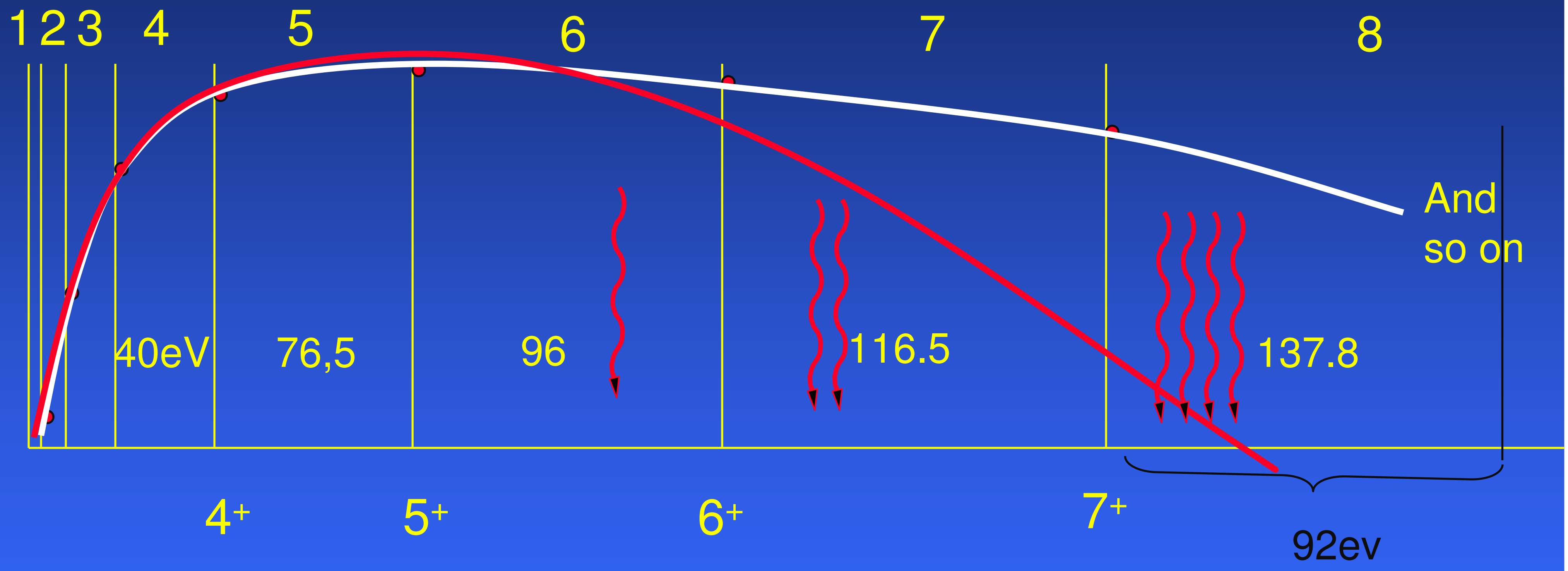
If Saha remains present



$$= (n_e/2)\ [h^3/(2\pi m_e k T_e)^{3/2}]$$

TU/e

Influence radiation



$$= (n_e/2)\ [h^3/(2\pi m_e k T_e)^{3/2}]$$

TU/e

For increasing Z
there will be a stage for which radiation escape
will disturb the ASDF

However these states are already low populated
No change in light generating properties

Purely Academic

Presence of $T_e = T_g$

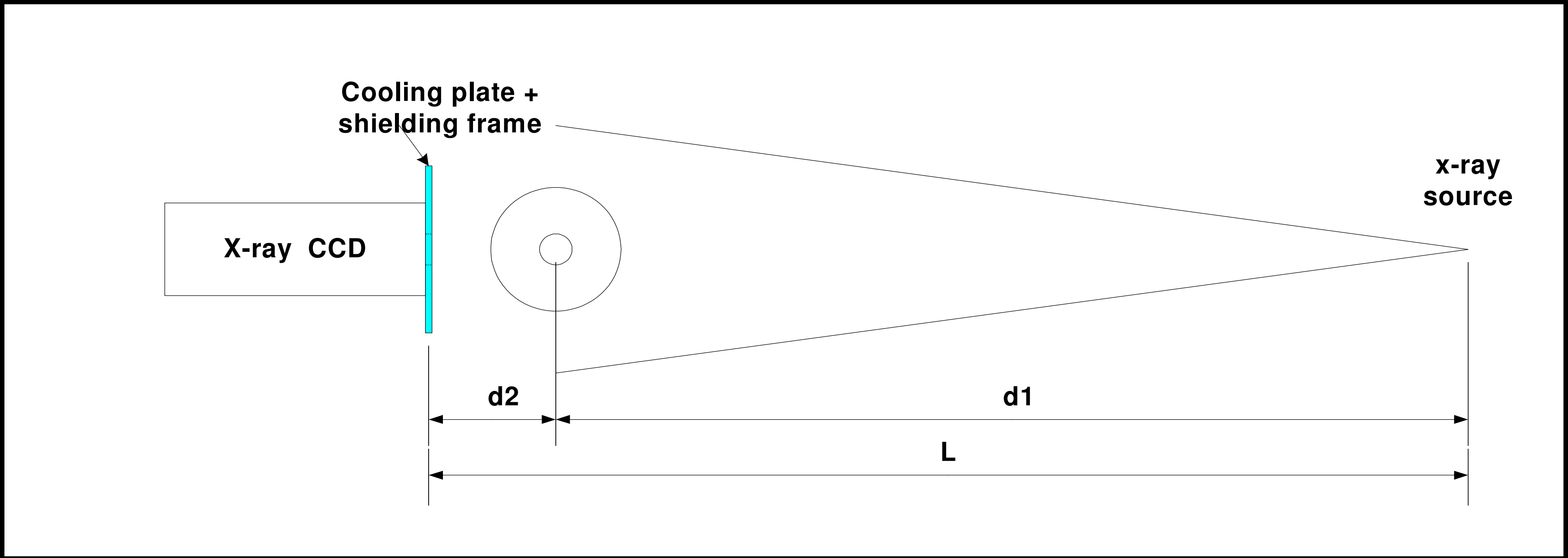
Relevant question for modeling

One- or two-Temperature plasma

Wanted two methods:	T_e	Thomson Sc
	T_g	Xray absorption

X-ray absorption

Xiaoyan Zhu, Tanya Nimalasuriya
Marco Haverlag; Evert Ridderhof



Procedure

Hg is dominant

$\nabla p / p << 1$

$\rightarrow$ $(n\,T)_{any\ pos} = (n\,T)_{wall}$

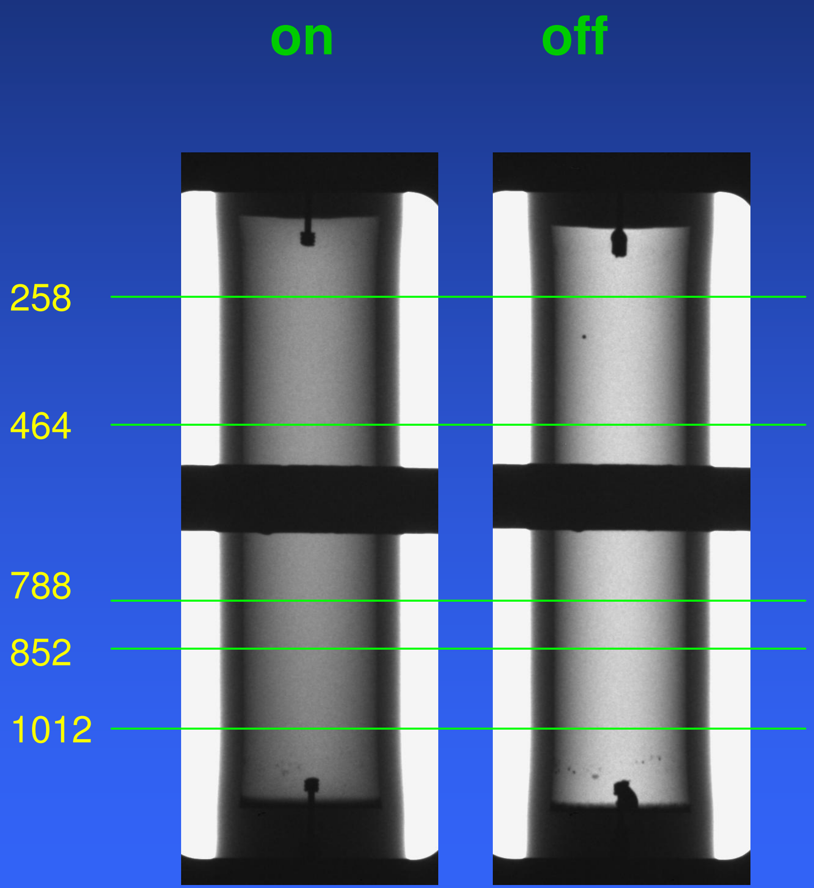
Xray

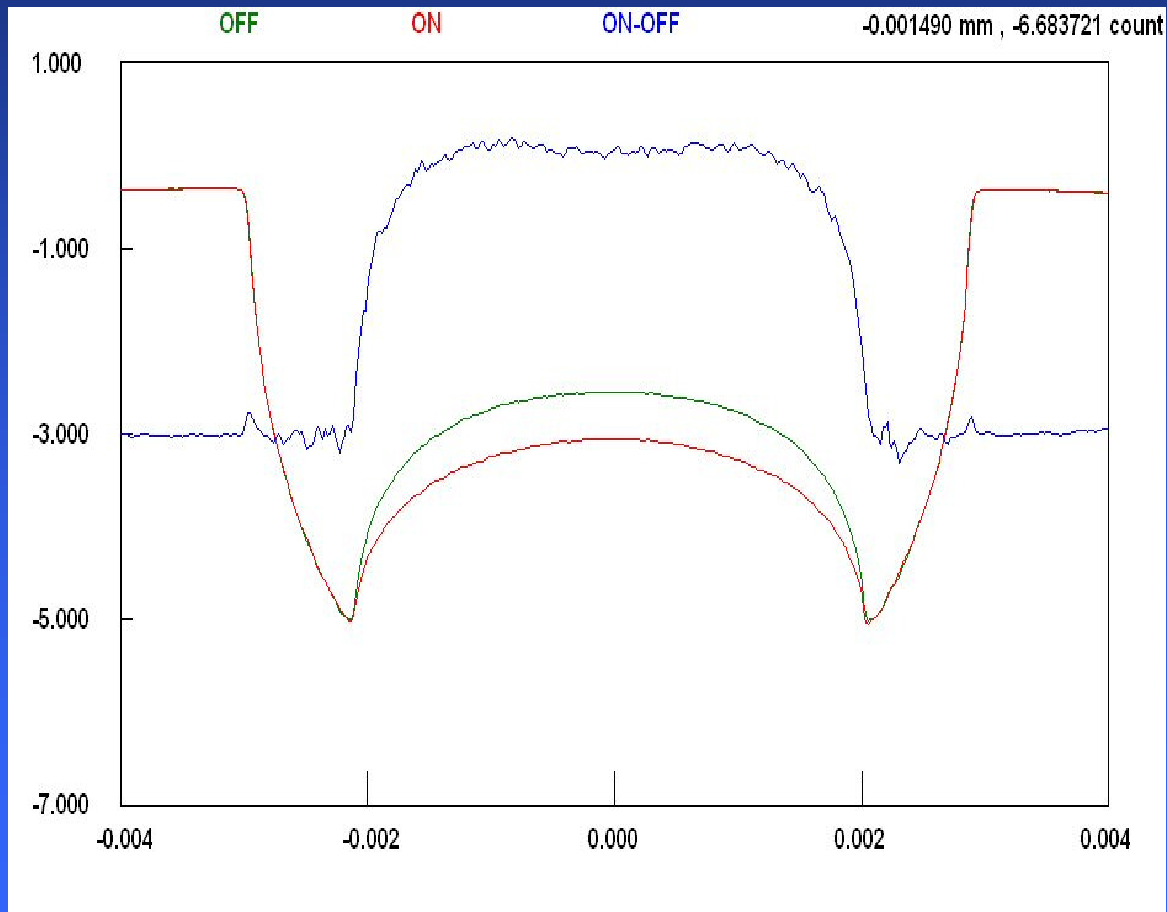
Pyrometer

T_g on any position

XRA on Helios lamp

- Exposure time: 200s.





TU/e

Thomson scattering:
expensive but always surprise surprise

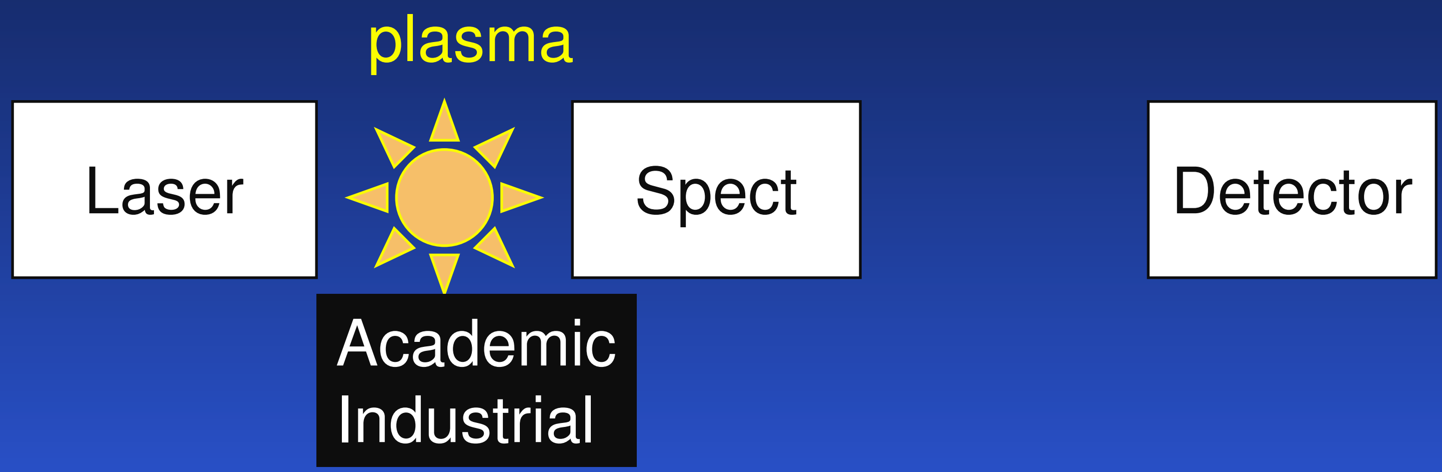
Expensive: Laser system + Spectrograph+ ICCD

Results: Interpretation independent non-equi model

Scattering on electron gas: Real n_e and T_e

Always a surprise

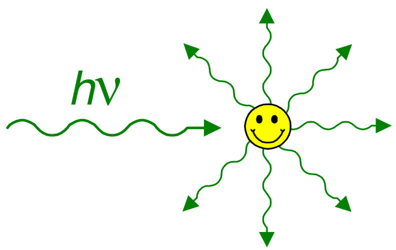
General structure set-up



1972	Ruby	Mono	PMT-array (7)
Xxx	xxx	xxxx	xxxx
1994	YAG	Mono	IPDA (1064)
2000	YAG	TGS (1eV)	ICCD (500x700)
2005	YAG (200 ps)	TGS (30eV)	ICCD ()

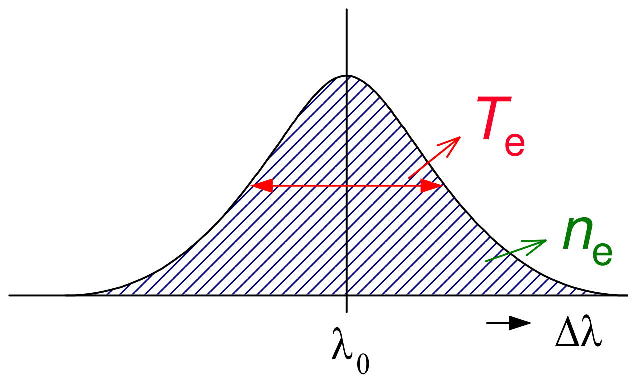
Thomson Scattering

⇒ scattering of photons on free electrons in a plasma



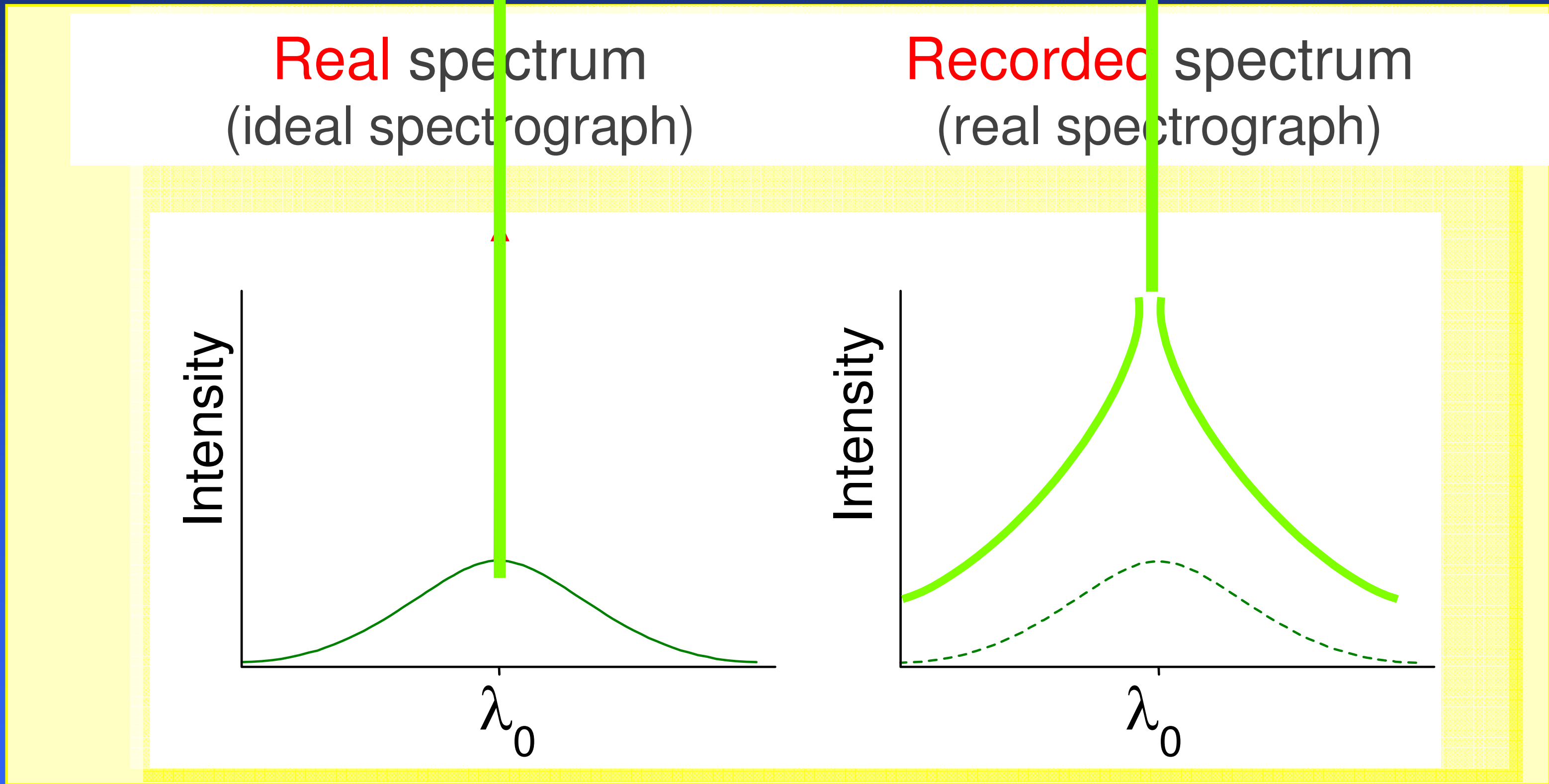
More **direct** measurement

Scattering intensity	Doppler broadening
⇩	⇩
n_e	T_e

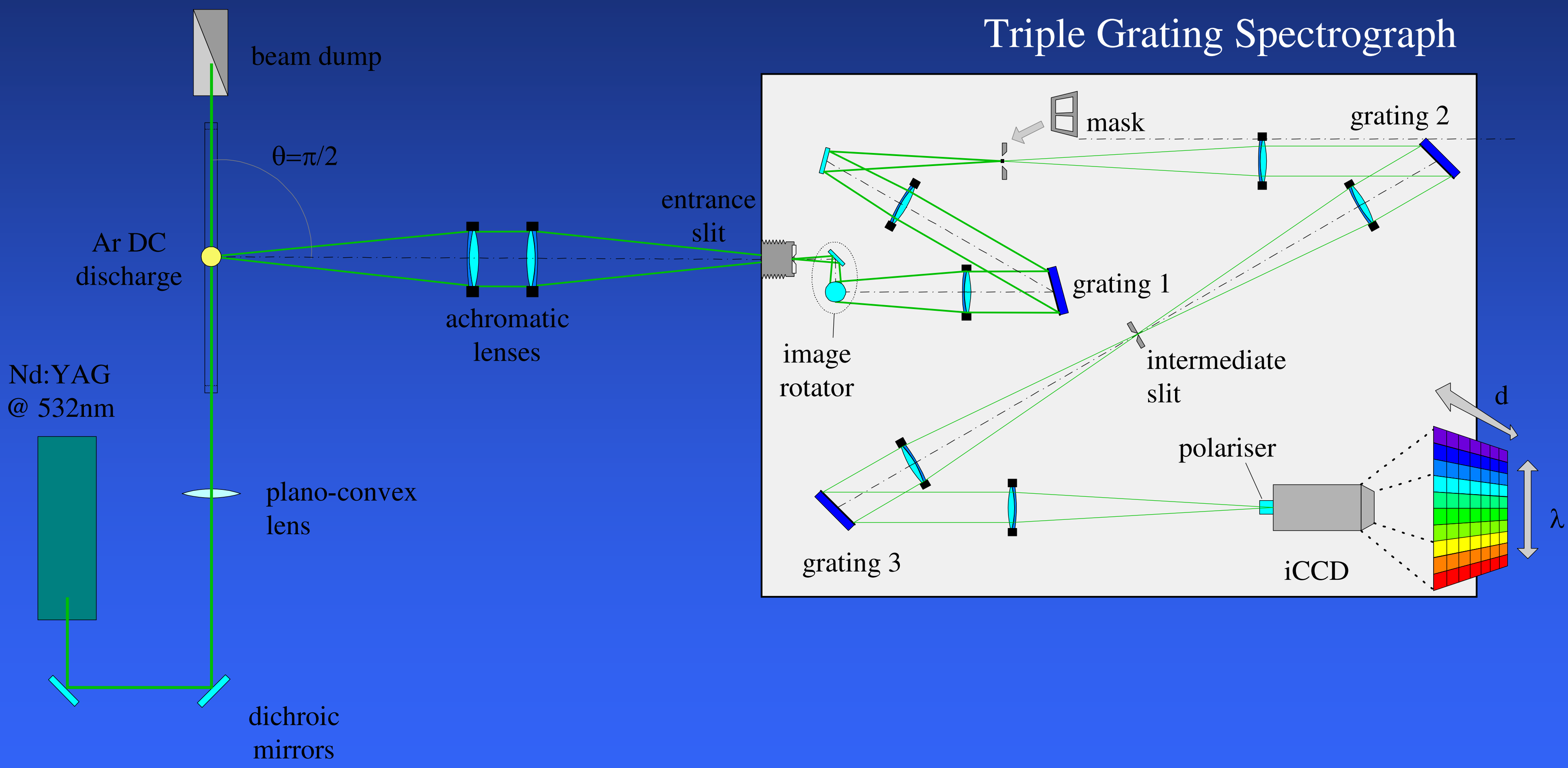


Redistribution of monochromatic light:

Instrumental profile



Triple Grating Spectrograph



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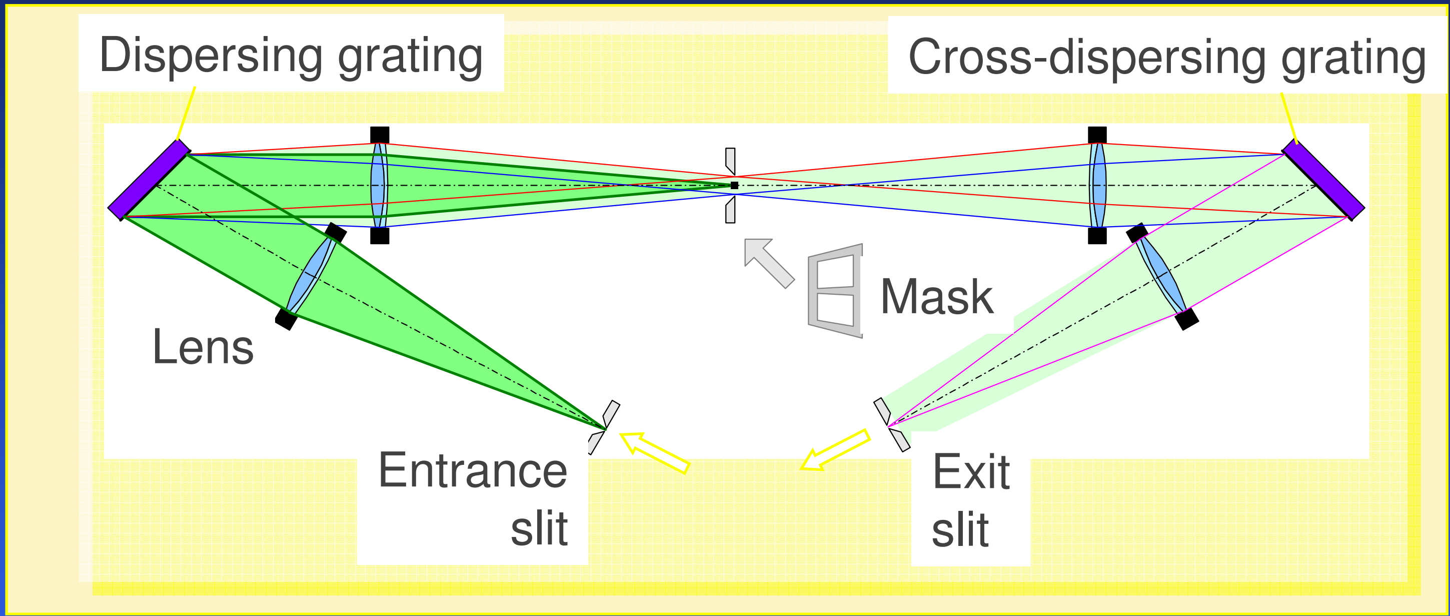
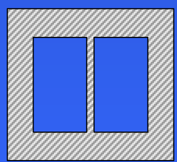
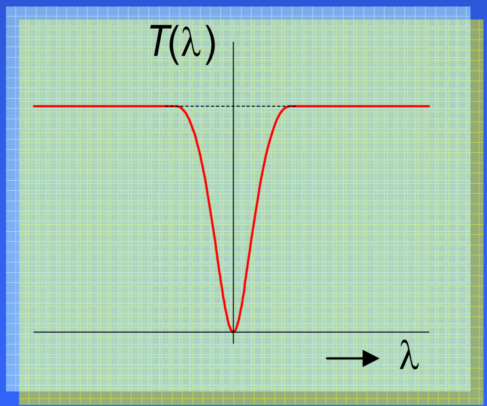
Home-made Filter



Mask



Transmission function



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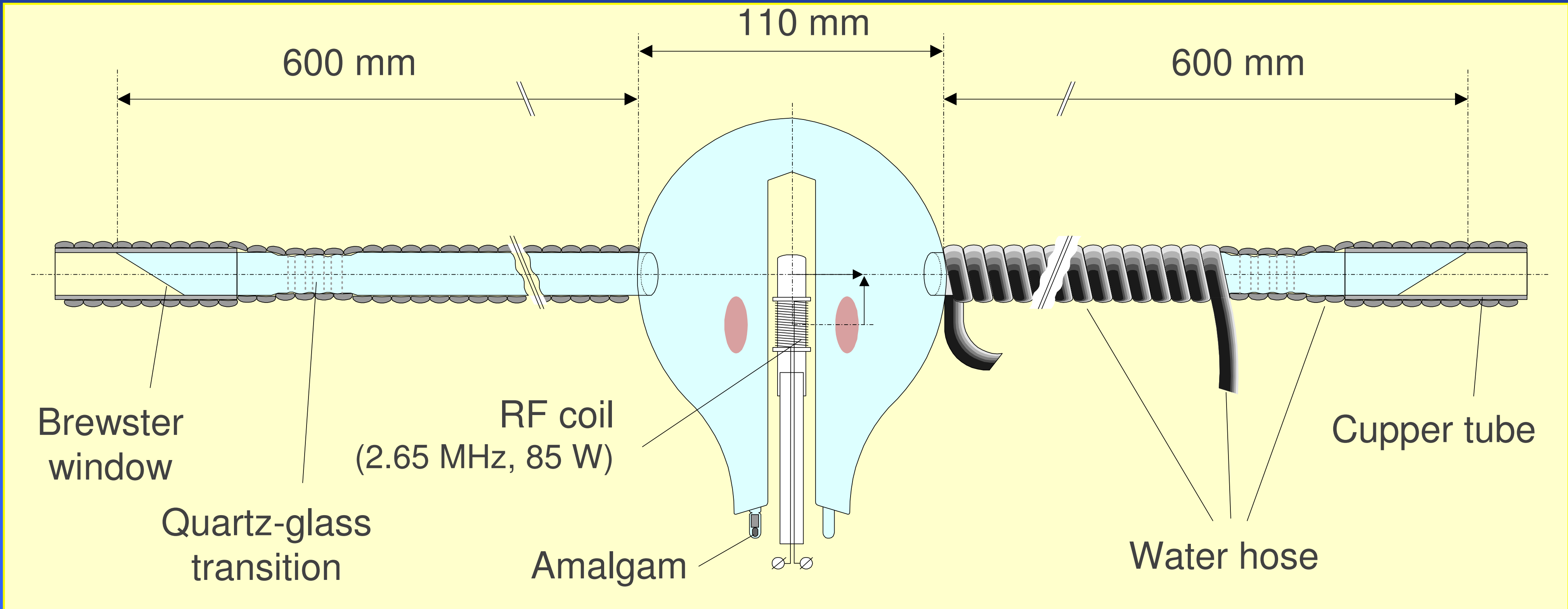
Experimental Version QL

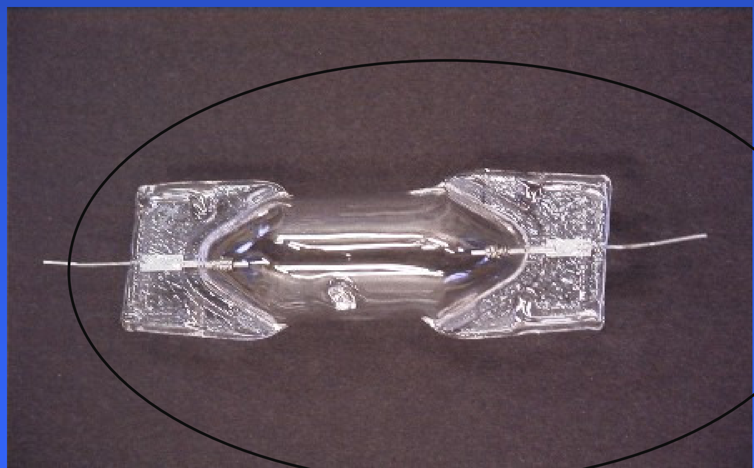
- Extension tubes
- Quartz, Brewster angle windows
- Heating
- Pressure correction



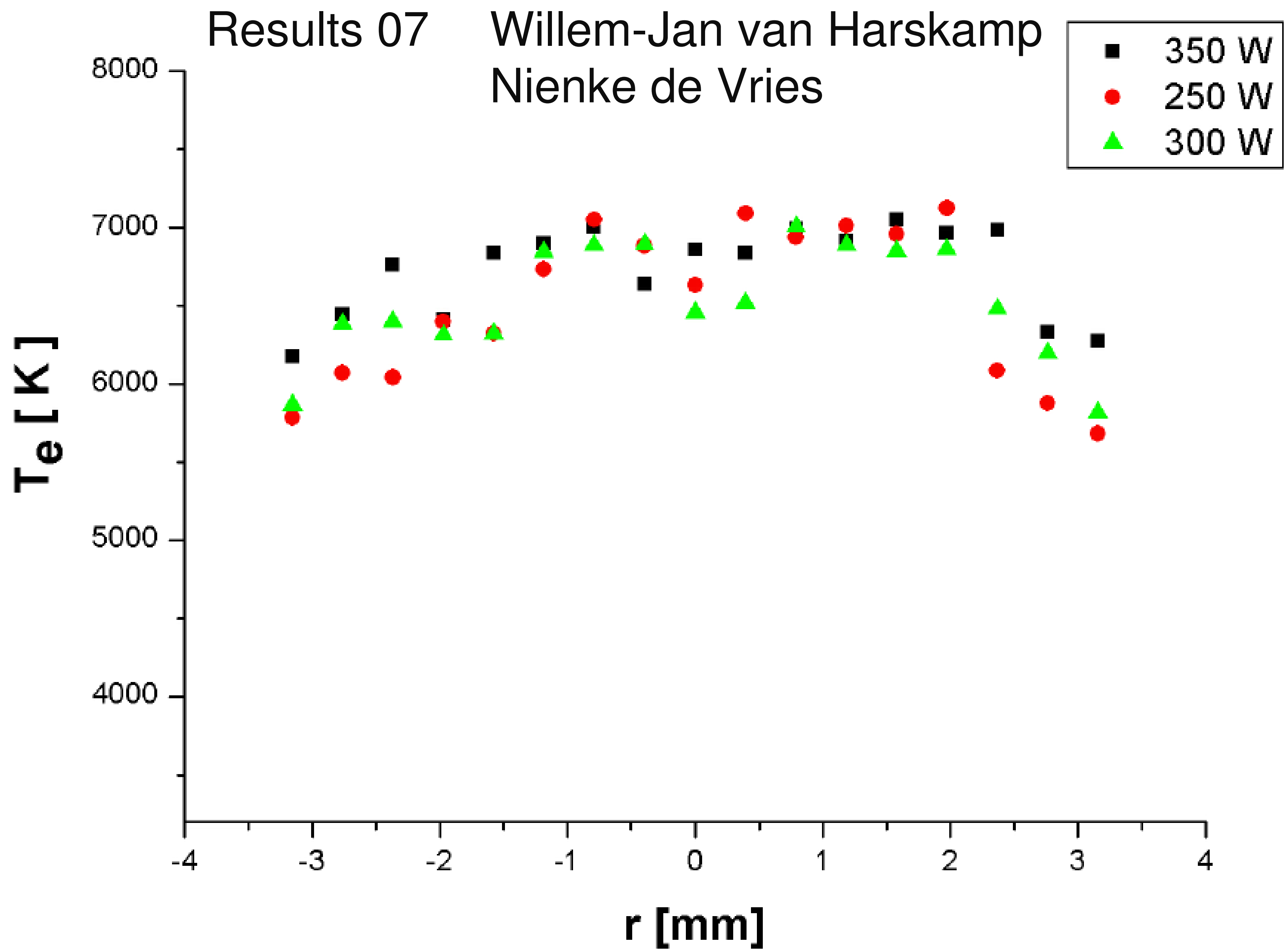
“Real” Lamp

400W high pressure Hg lamp

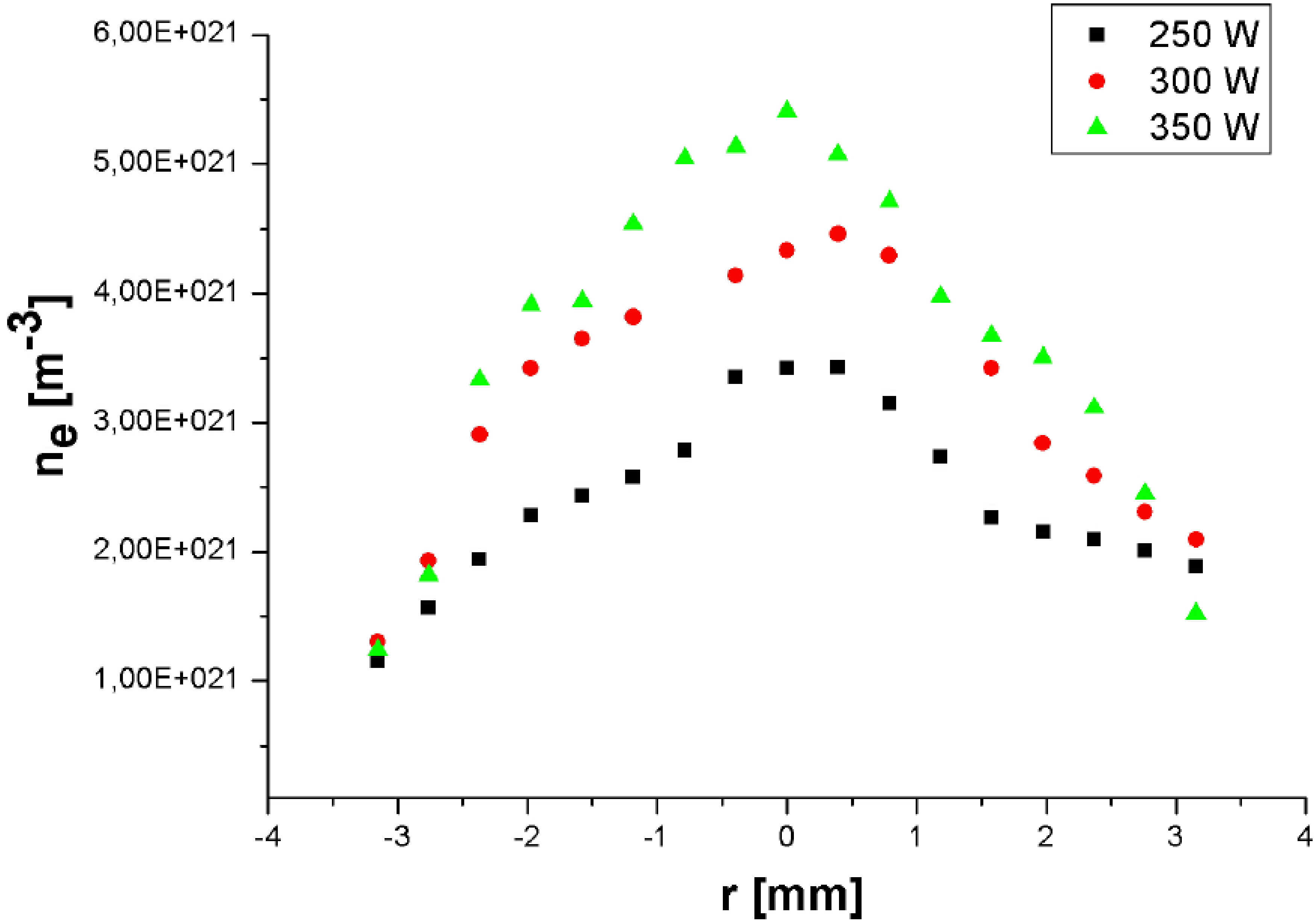
Inner diameter is 20 mm.



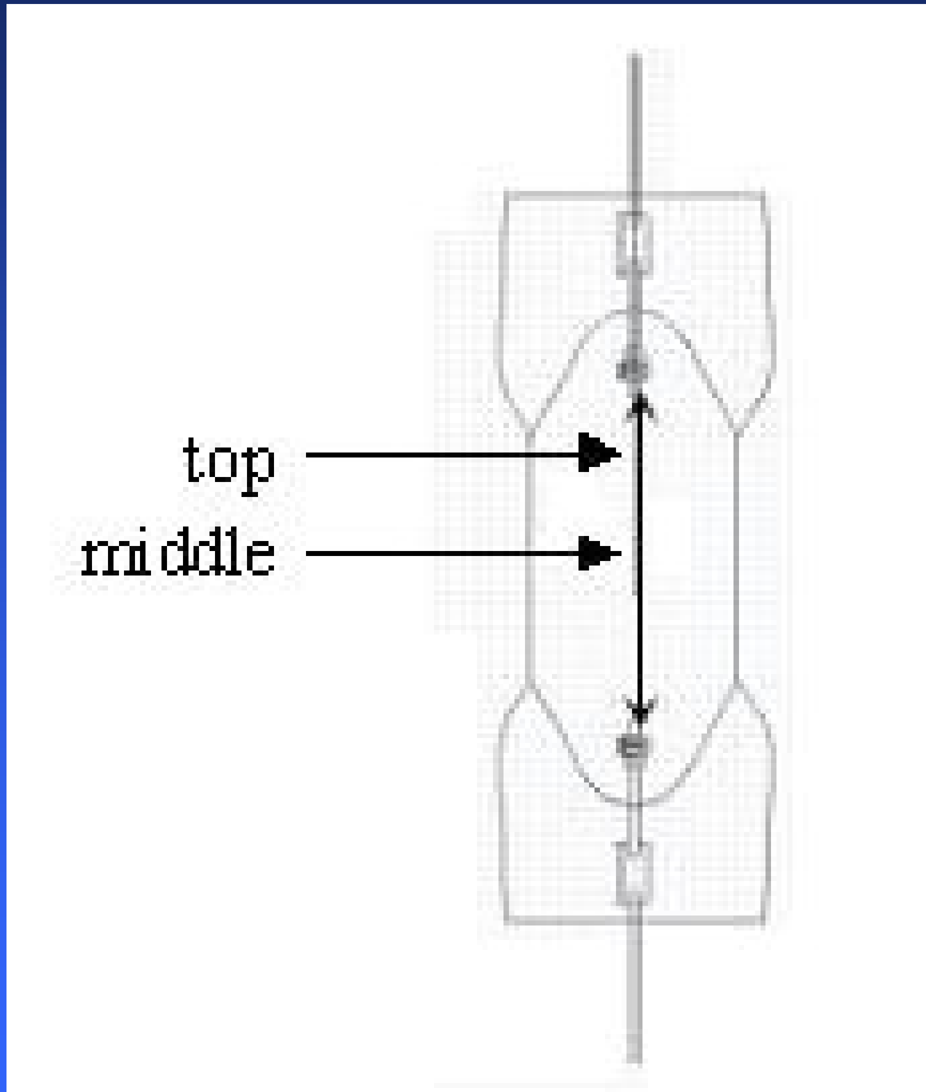
Note
Not a MH Lamp

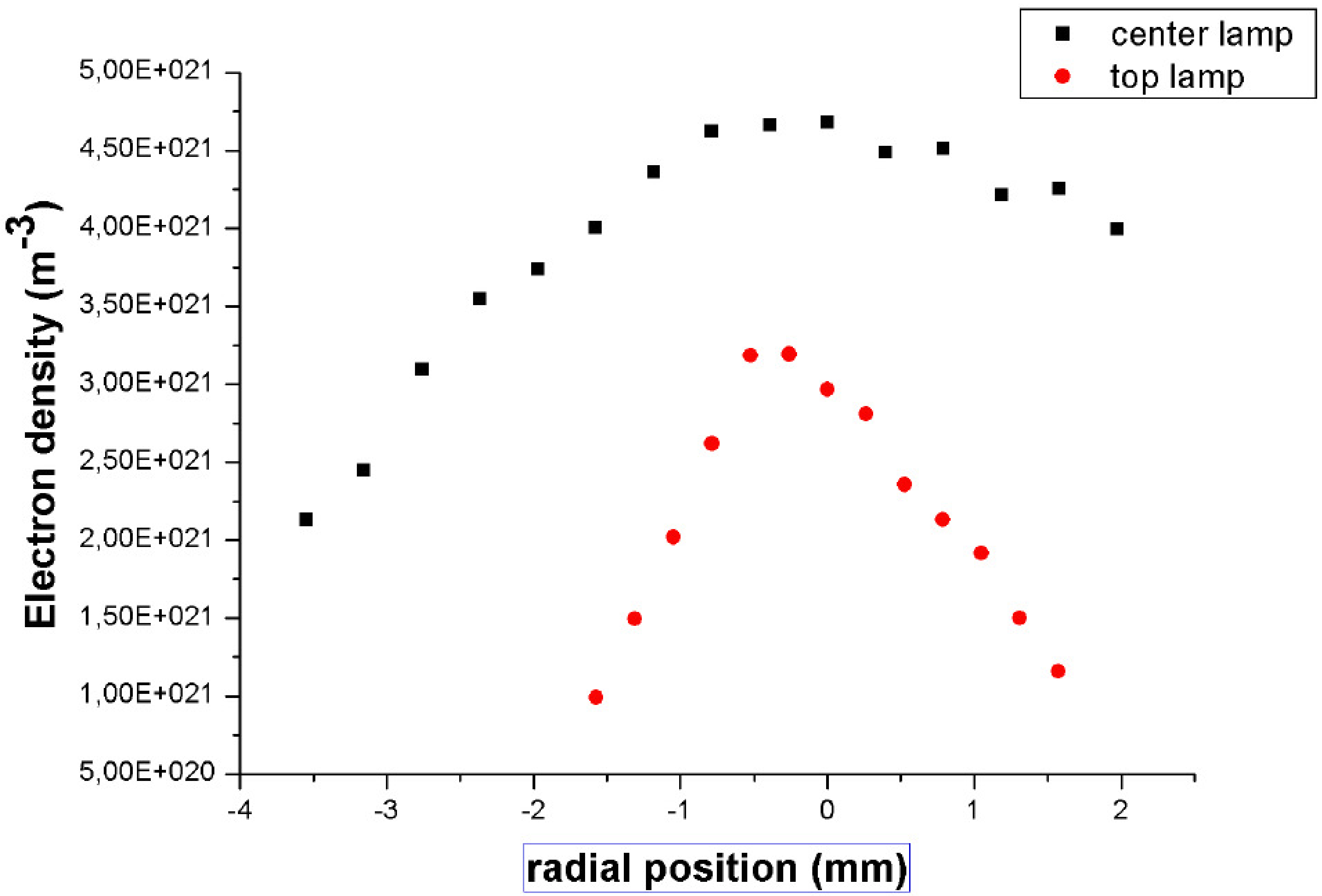


Results 07
Willem-Jan van Harskamp
Nienke de Vries
350 W
250 W
300 W
8000
7000
6000
5000
4000
T_e [K]
-4
-3
-2
-1
0
1
2
3
4
r [mm]

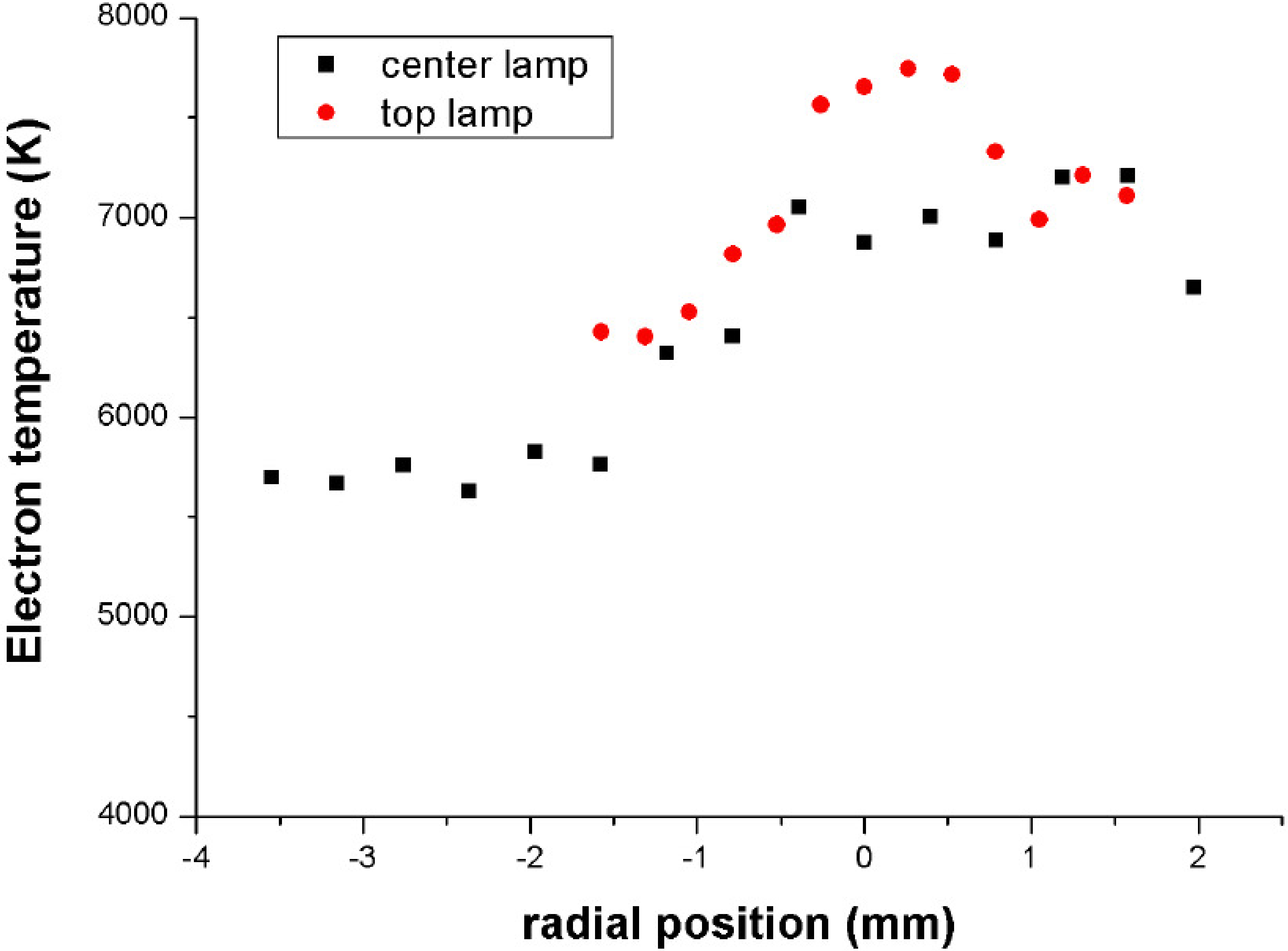


250 W
300 W
350 W
6,00E+021
5,00E+021
4,00E+021
3,00E+021
2,00E+021
1,00E+021
n_e [m^{-3}]
-4
-3
-2
-1
0
1
2
3
4
r [mm]


top
middle



center lamp
top lamp
5,00E+021
4,50E+021
4,00E+021
3,50E+021
3,00E+021
2,50E+021
2,00E+021
1,50E+021
1,00E+021
5,00E+020
Electron density (m-3)
-4
-3
-2
-1
0
1
2
radial position (mm)



Electron temperature (K)
8000
7000
6000
5000
4000
center lamp
top lamp
-4
-3
-2
-1
0
1
2
radial position (mm)

Deviation from equilibrium

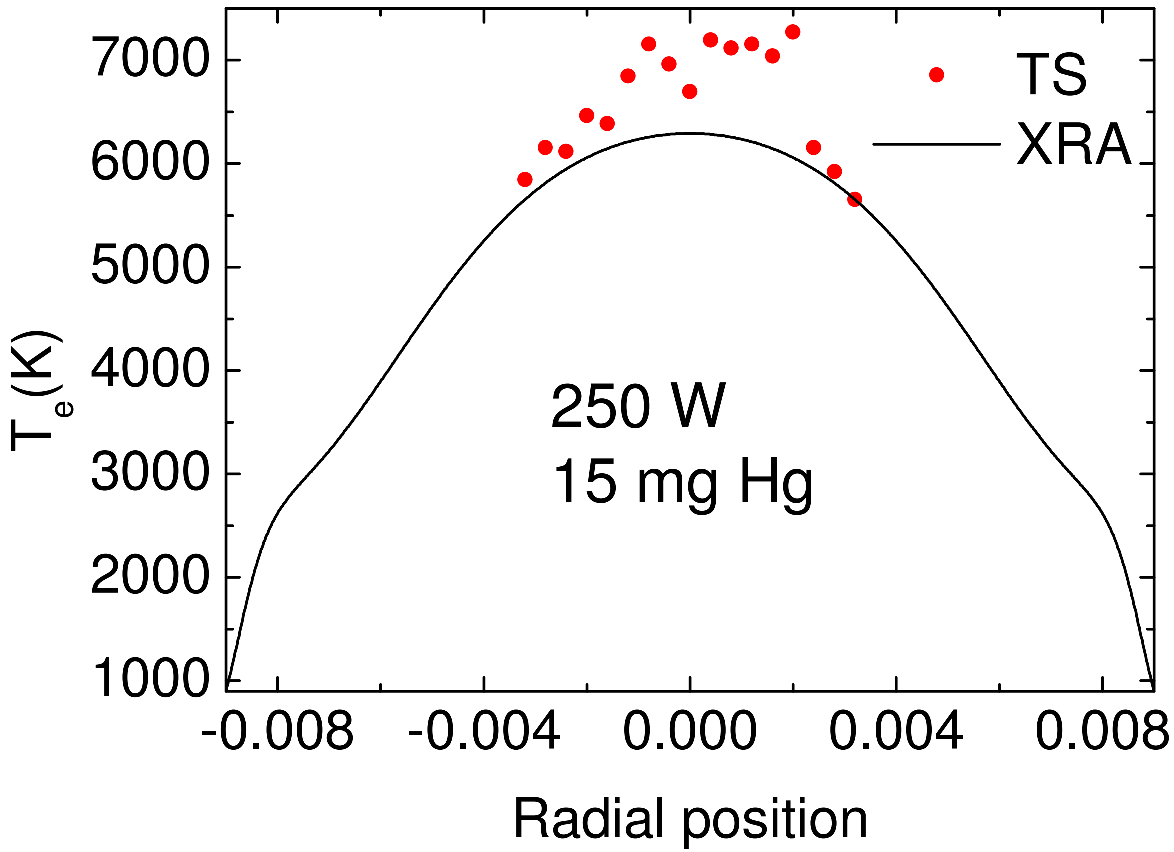
Usual philosophy: high pressures
high reaction frequencies; forward/backward
low diffusion velocities

so LTE present.

Type of departure: Thermal: $T_e \neq T_g$

Chemical: ionization degree

Comparison TS and XRA



Agreement within error bars?

Saha equilibrium

$$A_1 \longleftrightarrow A_1^+ + e$$

If Saha equilibrium present

$$n_1 = n_1^s = [n_e/2]\,[n_+/g_+]\,\{h^3/(2\pi m_e k T_e)^{3/2}\}\,\exp(I_1/kT)$$

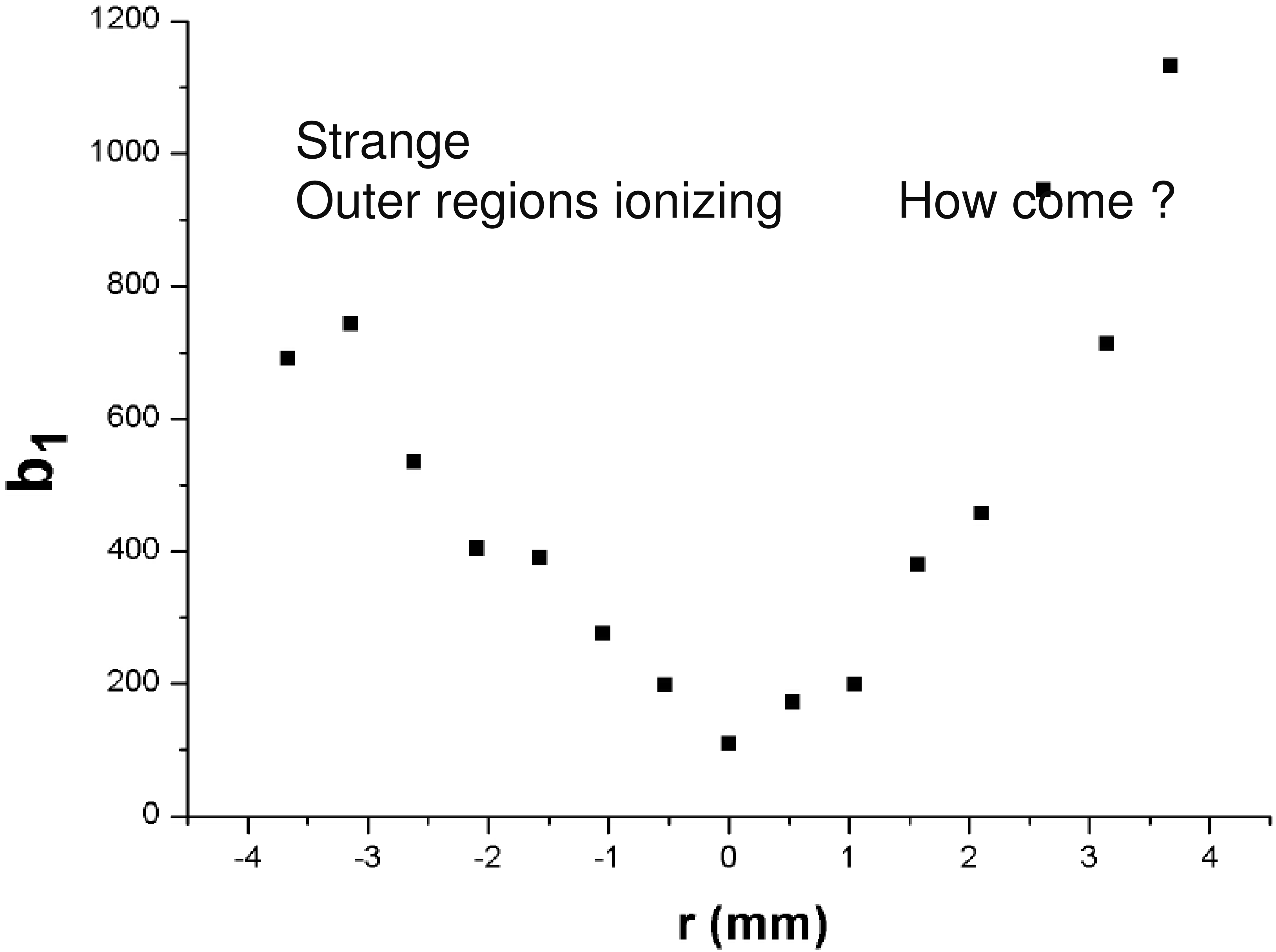
$n_1 = p/kT_g$

XRA

TS

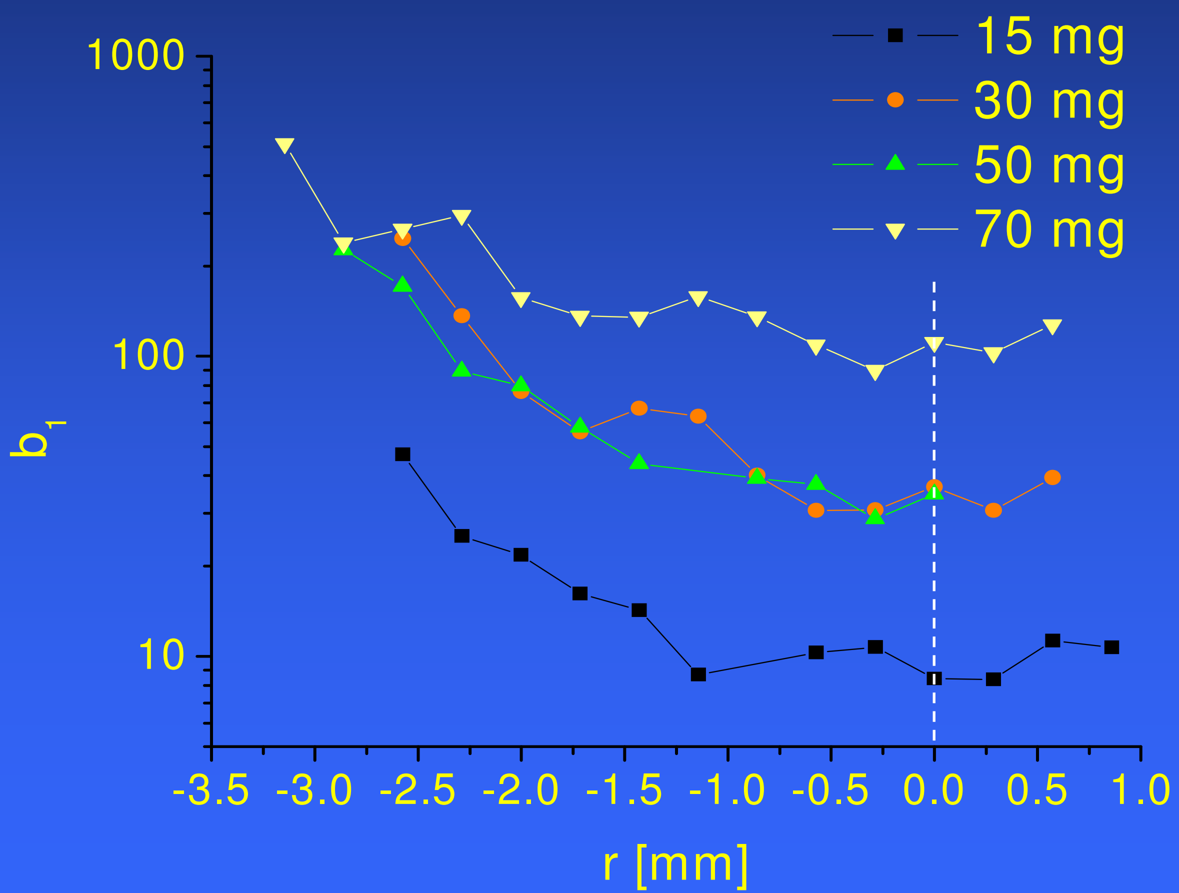
TS

$b_1 = n_1/n_1^s$ = 1 ??



Strange
Outer regions ionizing
How come ?
1200
1000
800
600
400
200
0
-4
-3
-2
-1
0
1
2
3
4
b_1
r (mm)

Chemical Equilibrium: b_1-factor different gas fillings



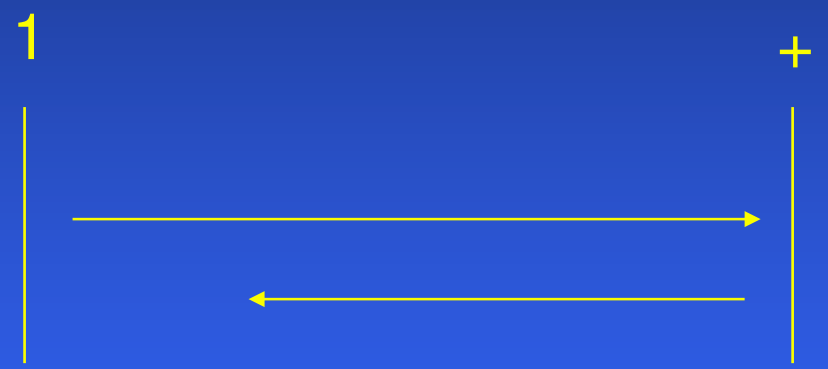
Increasing p

Deviations larger!!

Meaning $b_1 > 1$

$b_1 > 1$ implies $n_1 > n_1^s$ $\rightarrow$ ionization > 2e-recombination

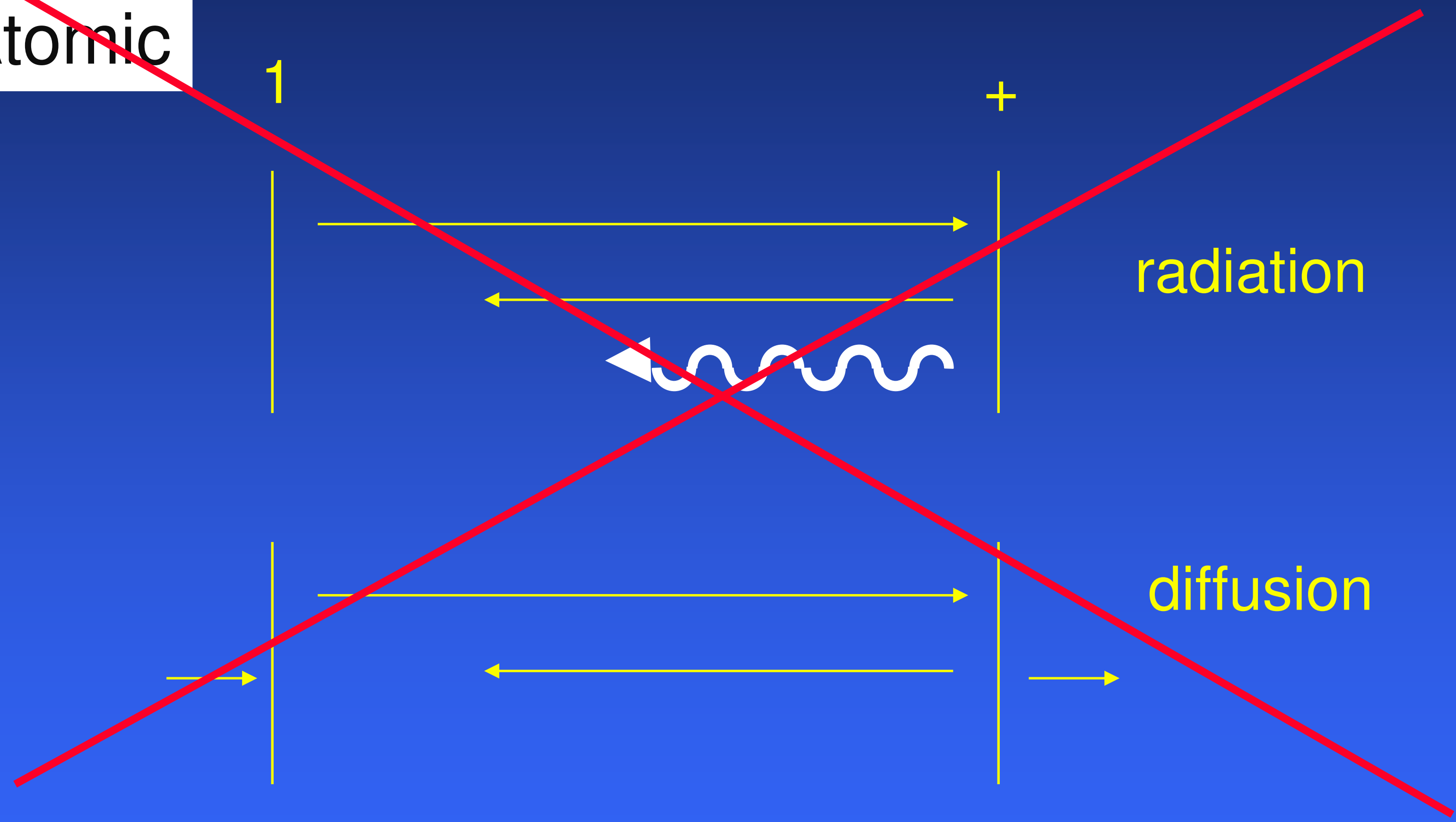
Not : ionization > recombination



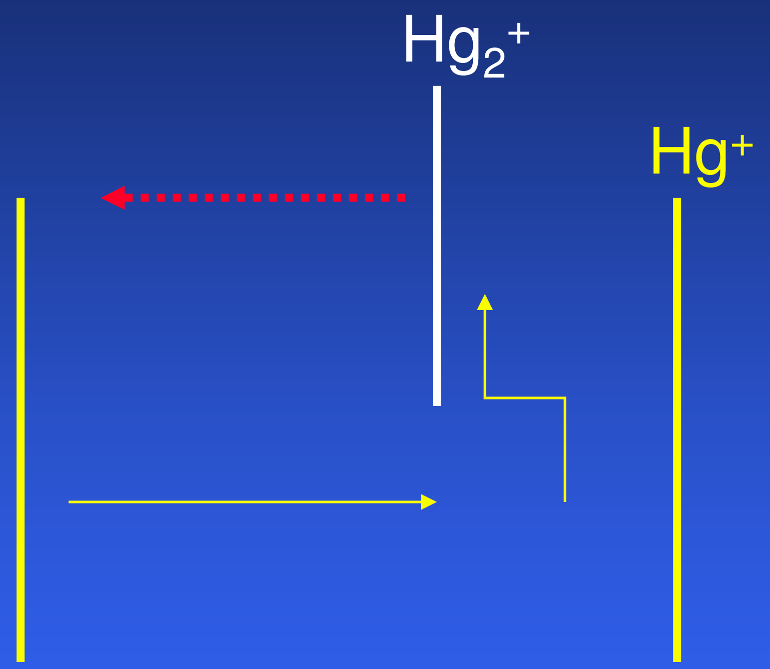
The ground state is relatively over-populated
The continuum is relatively under-populated

Possible Non- 2e-recombination

Atomic



The Role of Molecules



Transport in conversion space

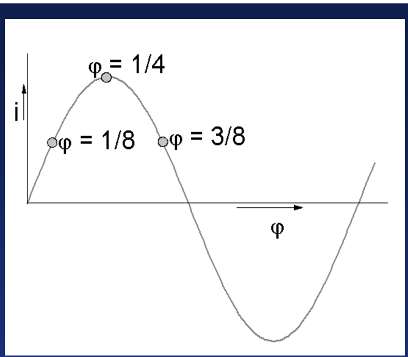
$$Hg^+ + Hg + e \rightarrow Hg_2^+ + e$$

$$Hg^+ + Hg + X \rightarrow Hg_2^+ + X$$

Followed by diss recom DR

$$Hg_2^+ + e \rightarrow Hg^* + Hg$$

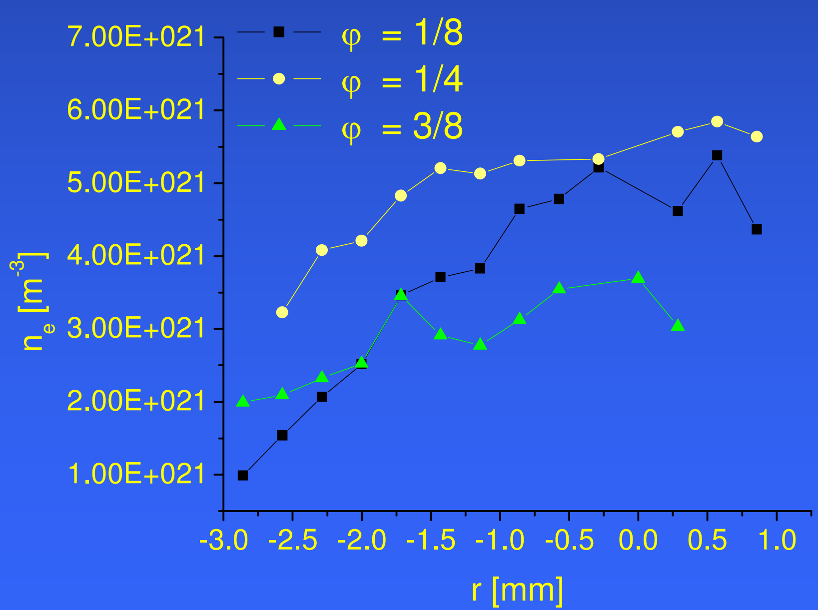
TU/e

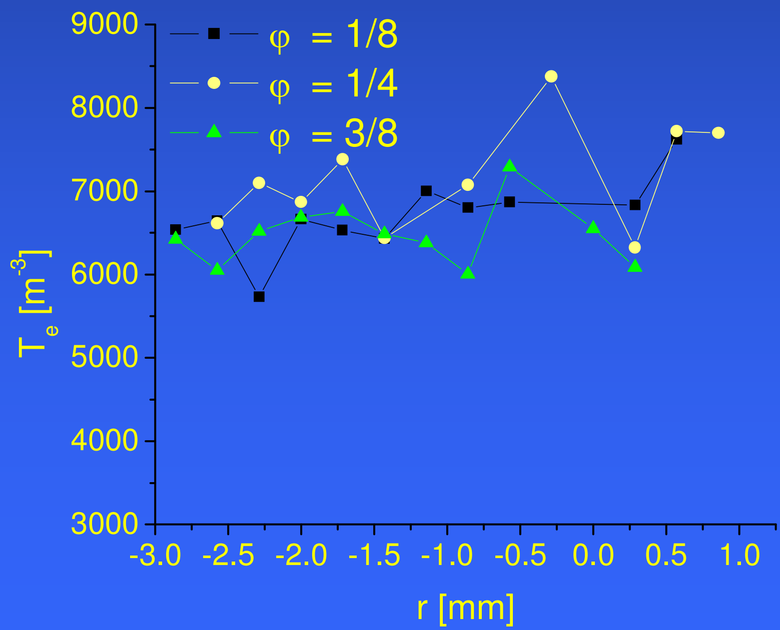


Time dependence TS

- Alternating Current: sine wave
- Radial profiles of n_e and T_e
  - different phases of the current

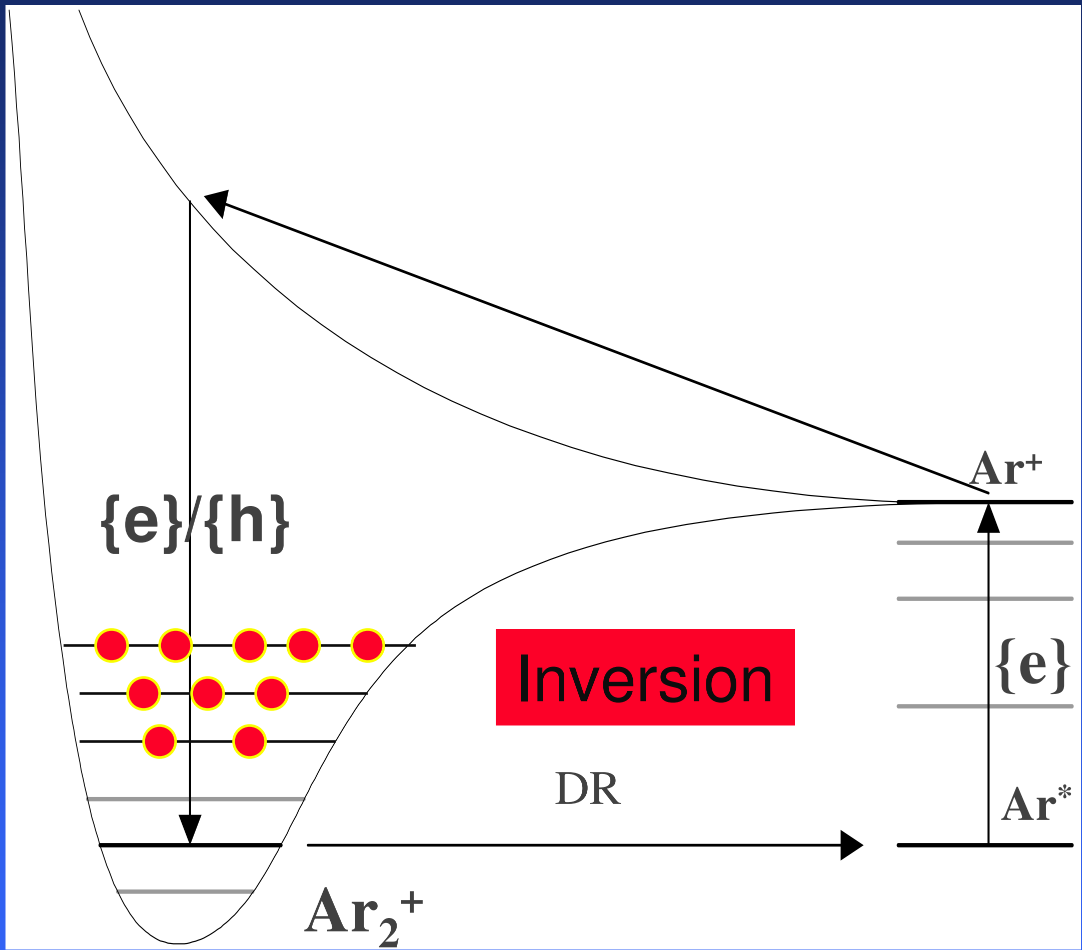
Variation in n_e
not in T_e





TU/e

What keeps the electrons hot??



Demand: High {e} heating

Known
DR fast

Solution:
Cyclic Process

Heating during
1) Recombination
2) Super-elastics

Considerations

Although electrons {e} are primary agents
They form a minority at boundaries and afterglows

The {h} heat reservoir is much large 3/2N kT

During association inversion possible

{f} heat reservoir is large as well

Transport

By radiation

In space

In conversion space

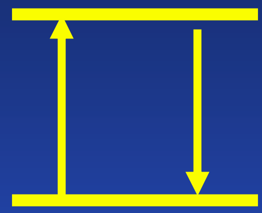
EEK

Are electrons the primary agents ??!!

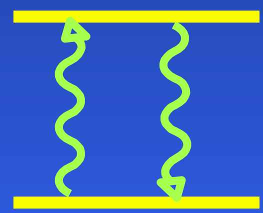
EEK electron excitation kinetics dominant !?

Competing Agents

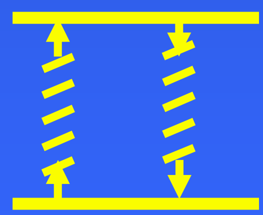
{e} EEK: Electron Excitation Kinetics



{f} REK: Radiation Excitation Kinetics

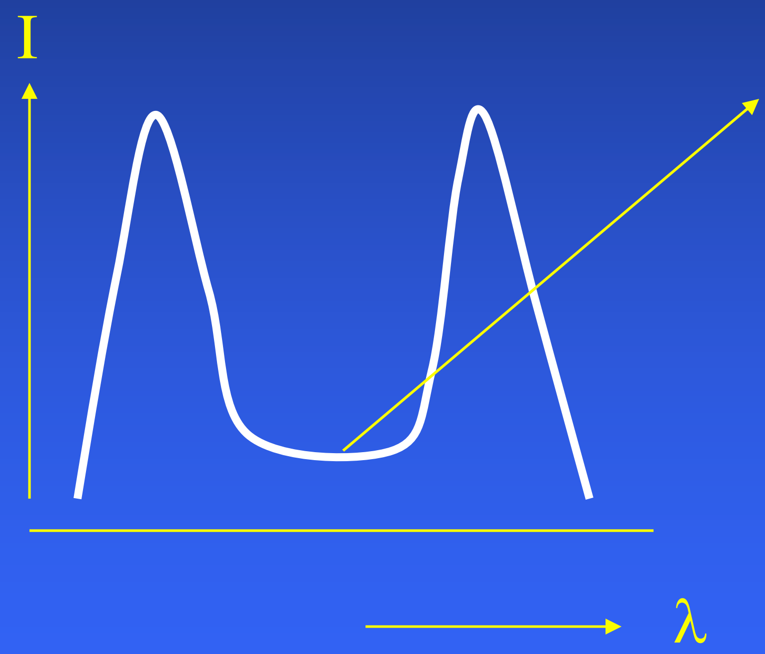


{h} HEK: Heavy particle Excitation Kinetics



Heating by radiation

Take 254 nm line



From edge

Question
How deep?

Irradiation of the plasma edge

Plasma center

Plasma Edge

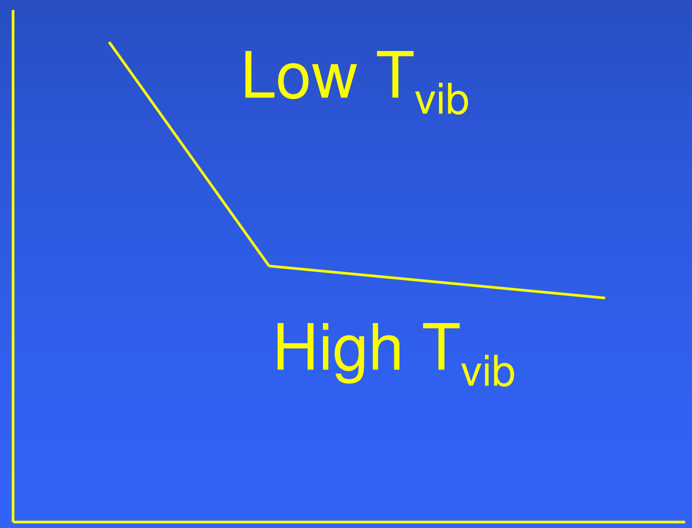
Local trapping
Planck Balance
Forced to equi

Radiation temperature
Impose
Boltzmann balance
Quasi equi

Molecular states

Known at the wall or afterglow
in time
in space

High population of highly vib states



Association via
Higher vibrational states

TU/e

The Sulfur lamp

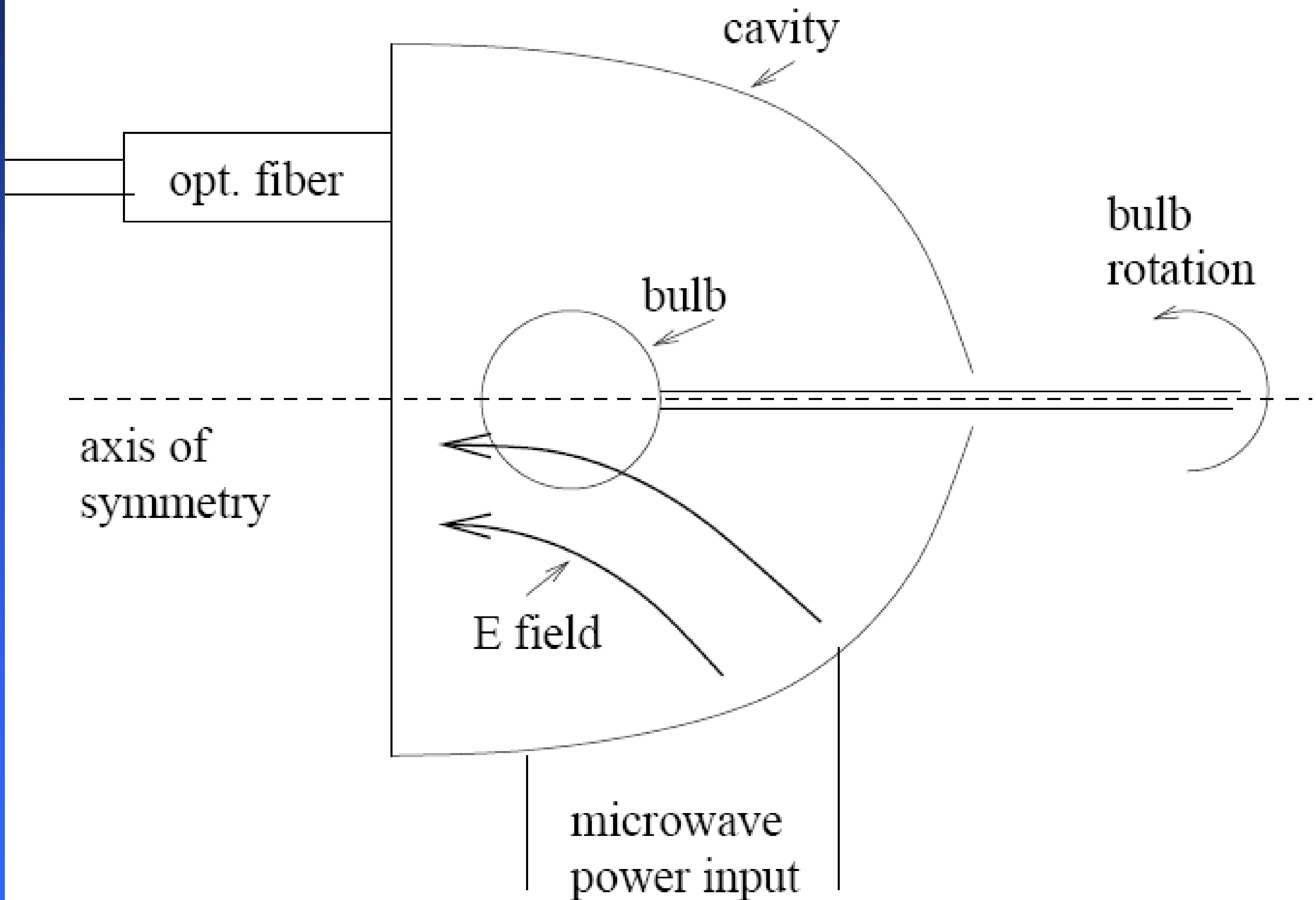
Harm van der Heijden	2003
Colin Johnston	2003

A microwave plasma — p = 10 bar
P = 1k Watt

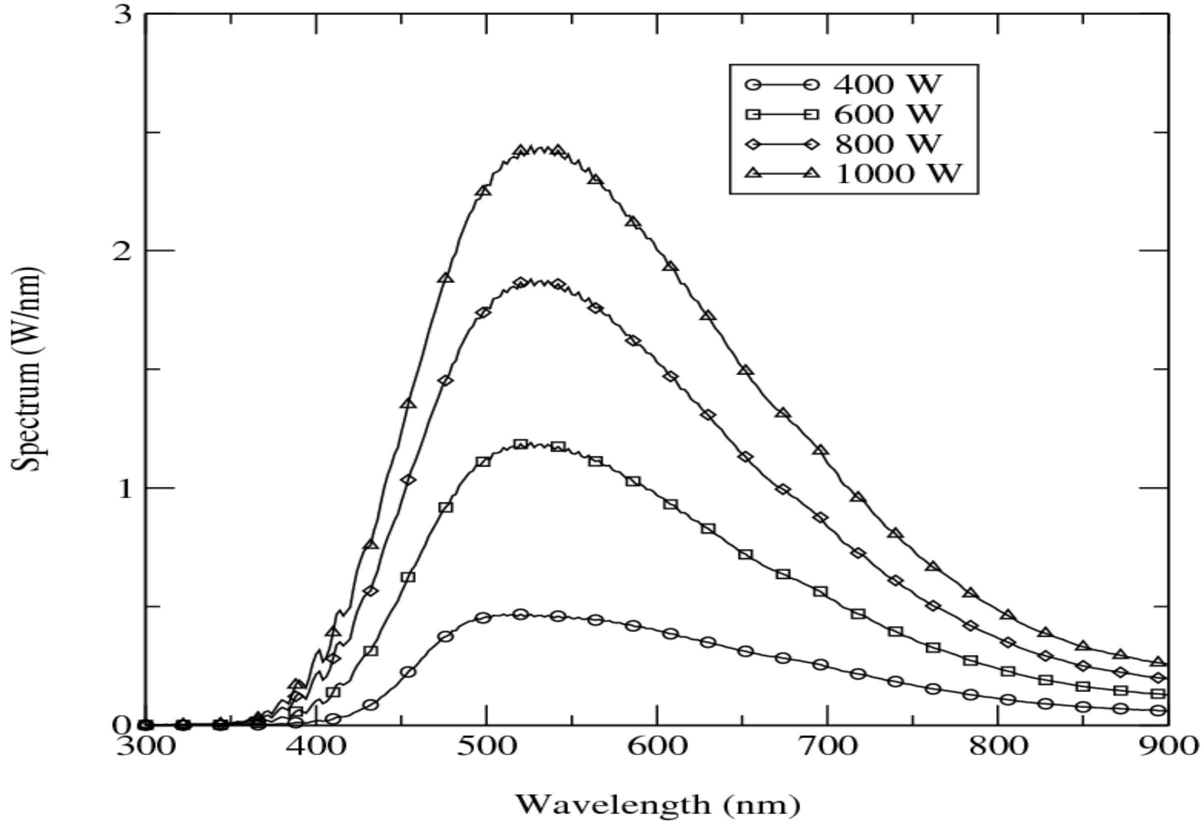
Experimental: not (laser) accessible
only passive spectroscopy

Modeling: LTE
microwave power coupling
heat conductivity
radiation generation and transport

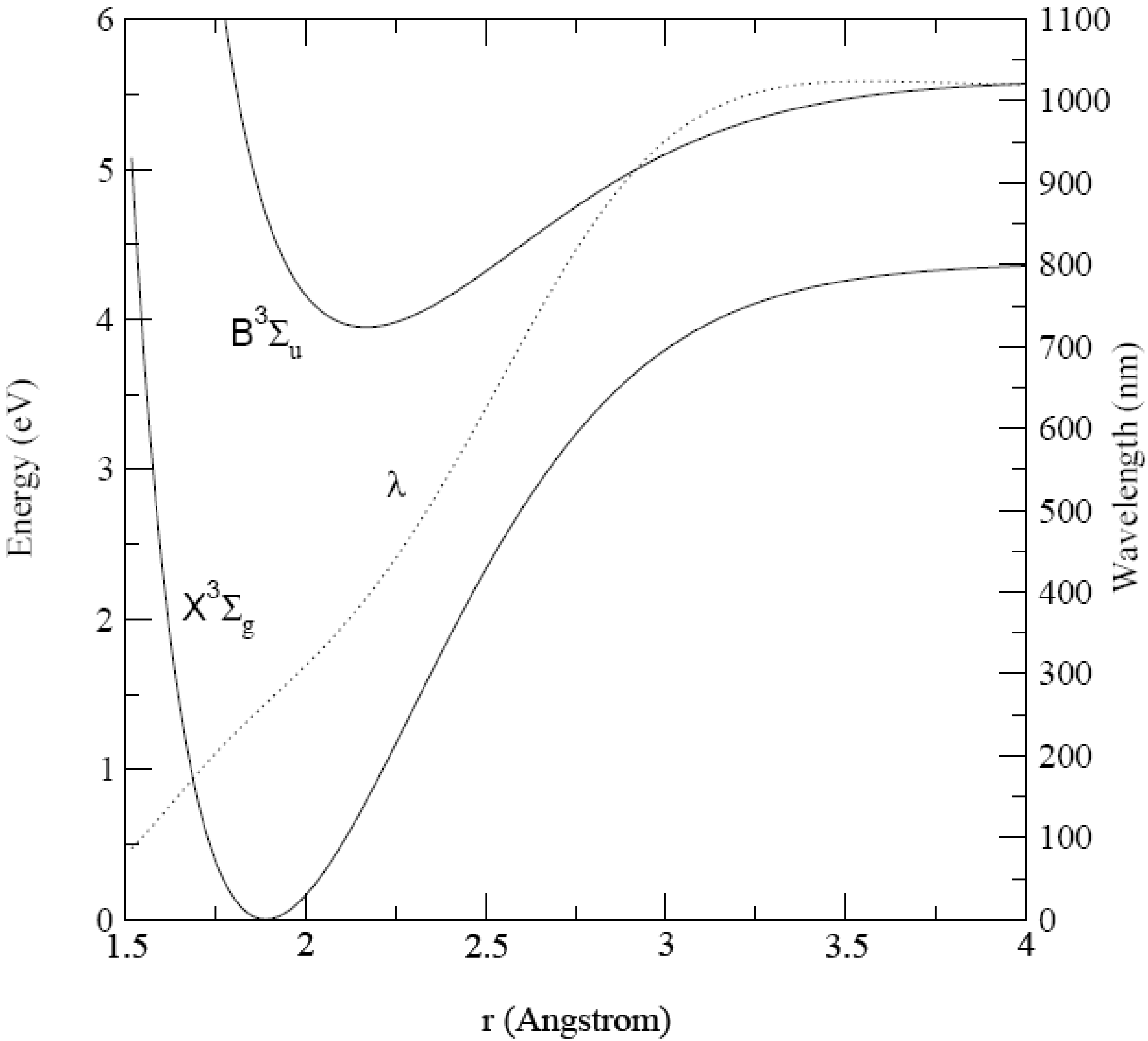
In 1992 a candidate for the illumination Sidney 2000



Matching the eye-sensitivity



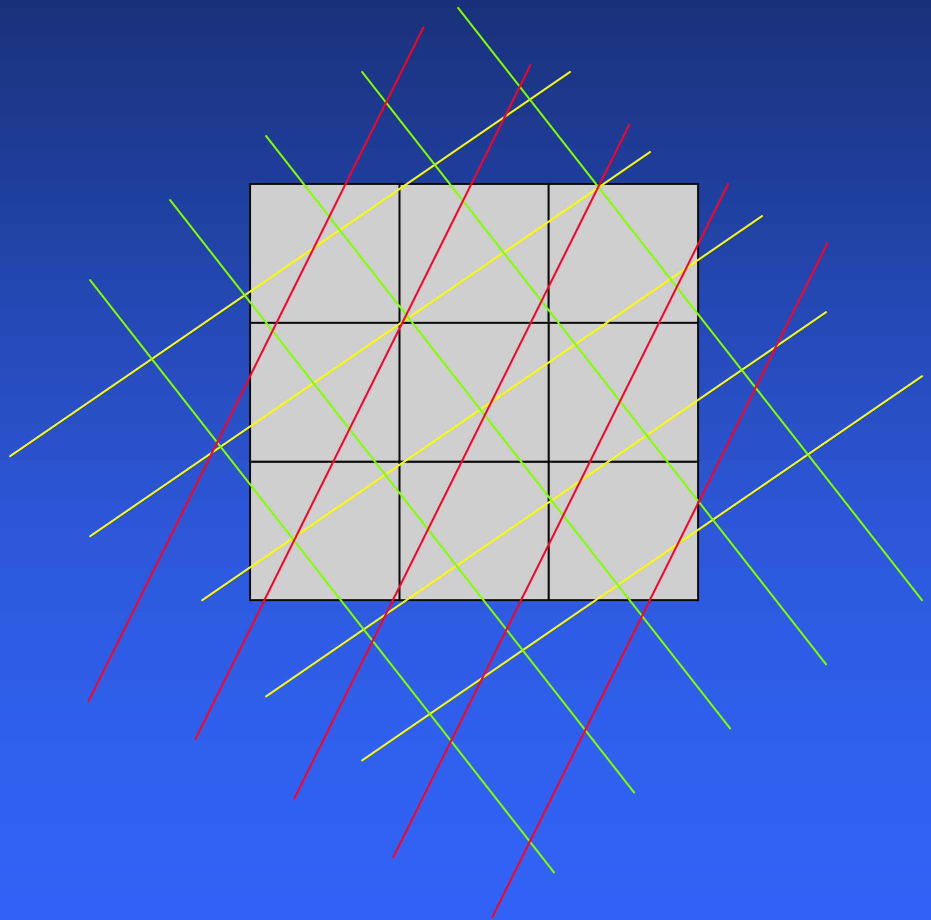
TU/e



6
5
4
3
2
1
0
1.5
2
2.5
3
3.5
4
1100
1000
900
800
700
600
500
400
300
200
100
0
Energy (eV)
Wavelength (nm)
r (Angstrom)
$B^3\Sigma_u$
$X^3\Sigma_g$
λ

TU/e

Radiation: Ray Tracing

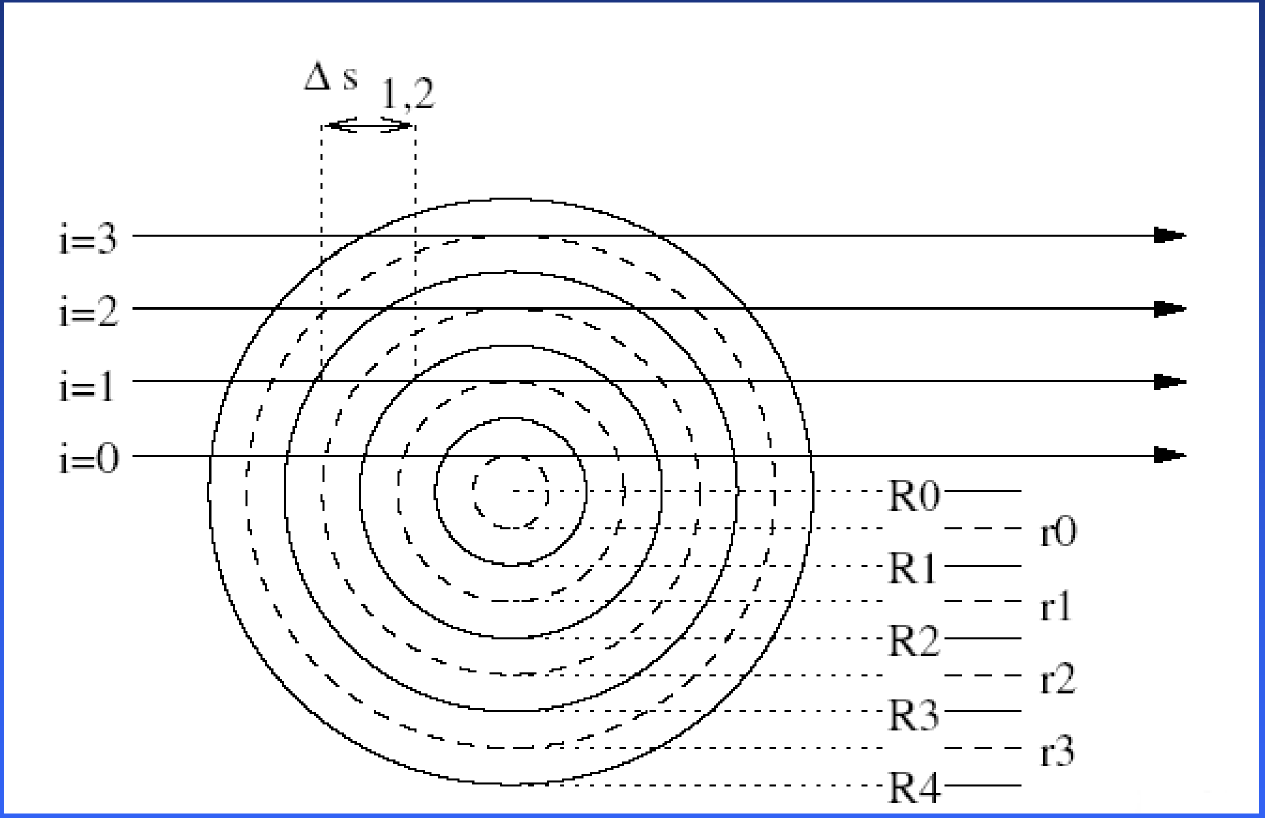


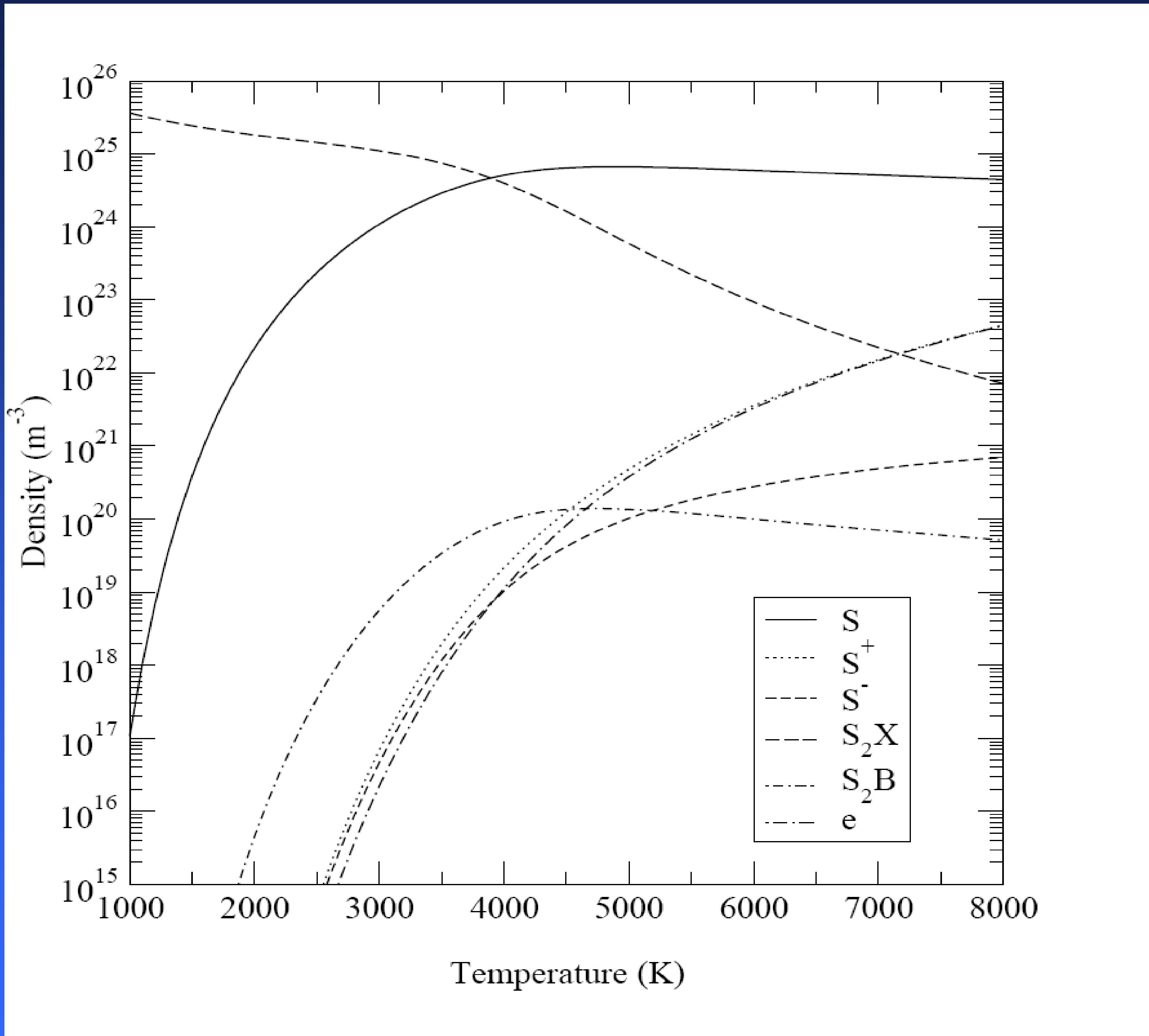
Evolve

$$dI_\nu(\nu)/ds = j_\nu - k(\nu)I_\nu(\nu)$$

- For different lines
- Different υ -values
- Compute plasma irradiation
- Solve Fluid equation
- Find new $k(\upsilon)$ and $j_\upsilon(\upsilon)$
- Evolve Radtrans eqn again
- Etc.

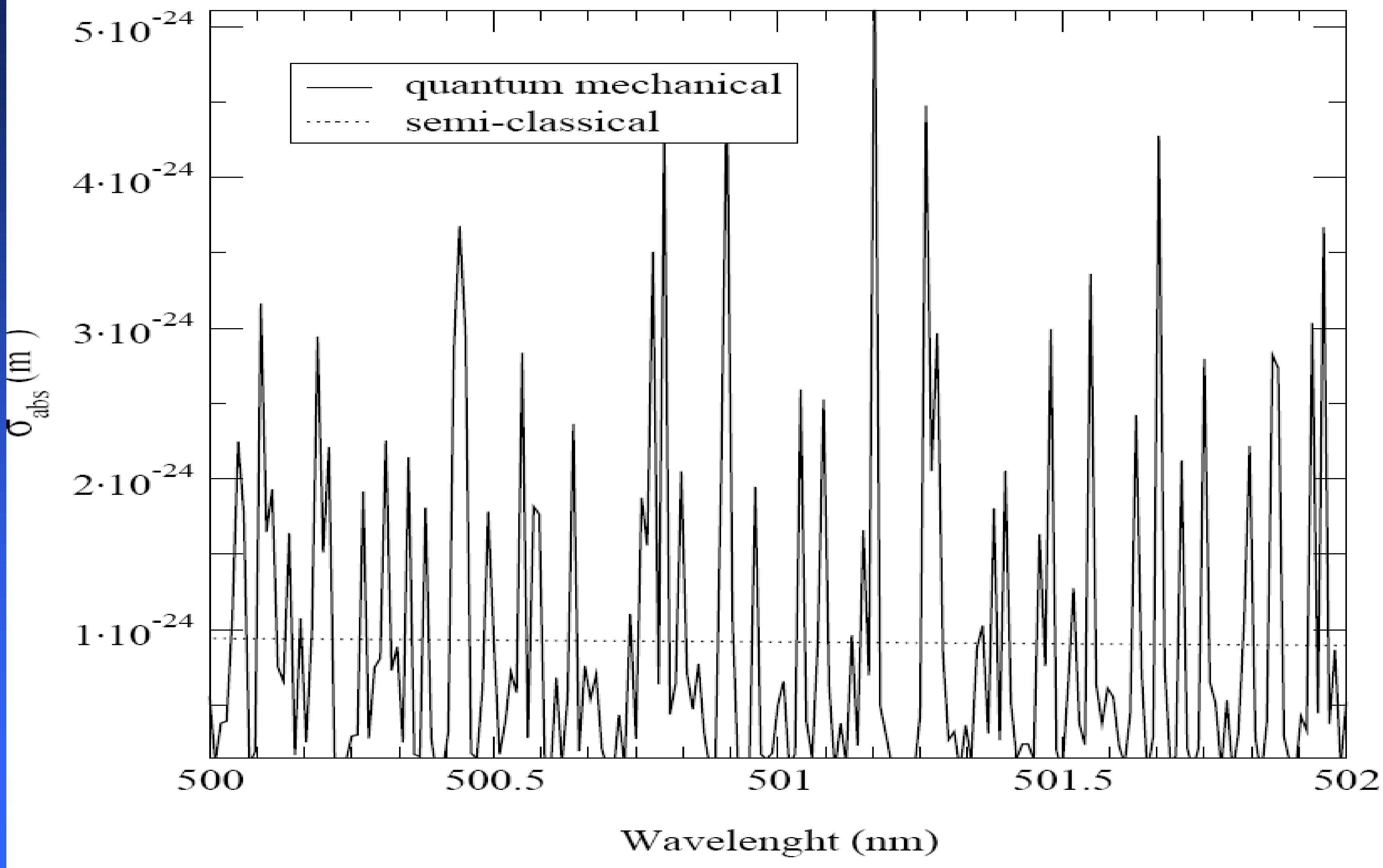
Using Symmetry



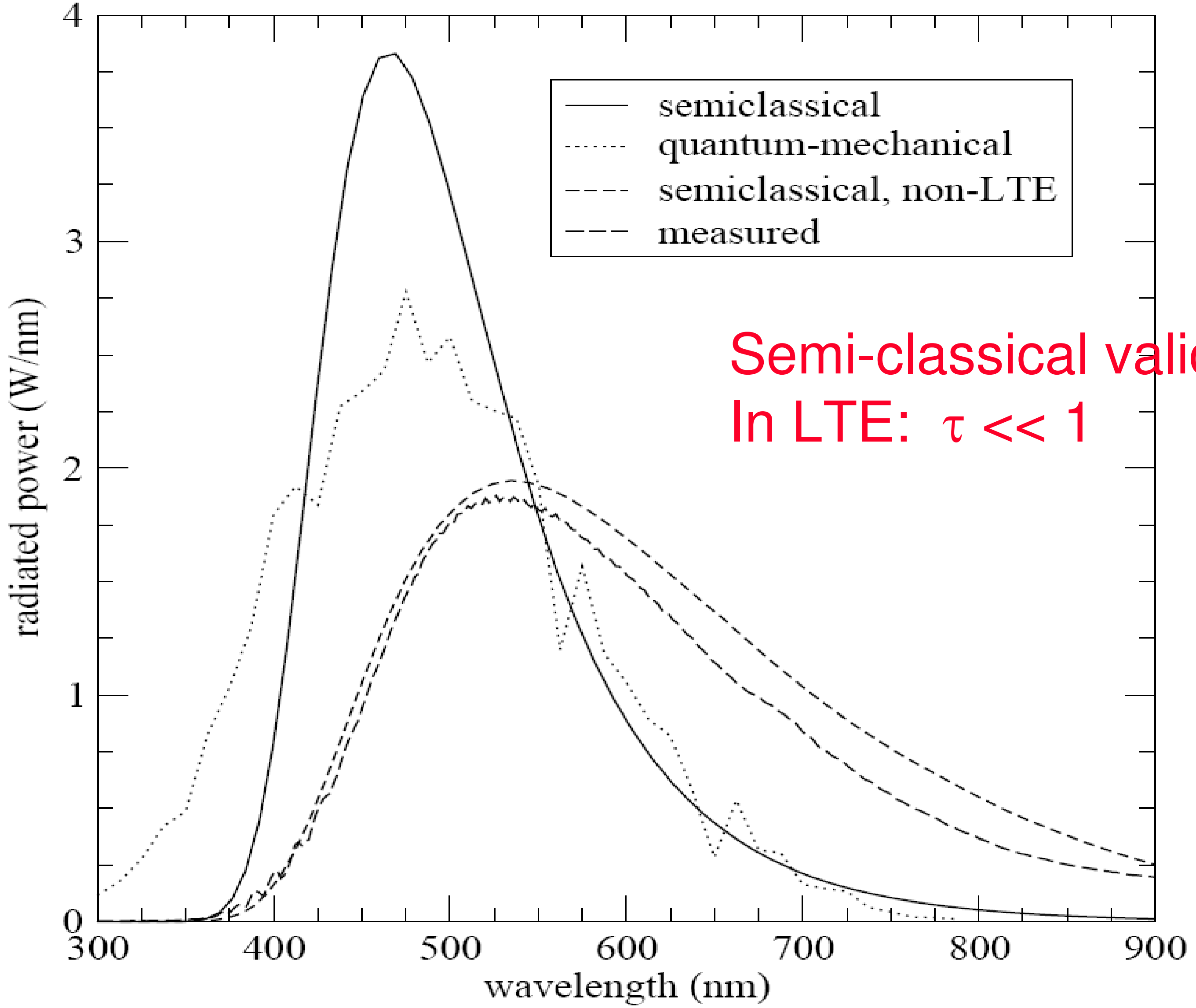


Density (m^-3)
10^26
10^25
10^24
10^23
10^22
10^21
10^20
10^19
10^18
10^17
10^16
10^15
1000
2000
3000
4000
5000
6000
7000
8000
Temperature (K)
S
S^+
S^-
S_2X
S_2B
e

TU/e



quantum mechanical
semi-classical
5·10-24
4·10-24
3·10-24
2·10-24
1·10-24
σabs (m)
500
500.5
501
501.5
502
Wavelenght (nm)



Semi-classical valid
In LTE: $\tau << 1$

Main result

The IR excess can (only) be explained
By a non-equi distribution of the rot-vib population

B-Molecules are formed in higher states
During coll-decay to lower state radiation takes place

Inversion in the B molecule !!

Evidences for high-pressure non-LTE

CO_2 and CO lasers.

Sulfur lamp

Ball-lightening

Pink Afterglow N_2

Concluding

High pressure does not guarantee Equilibrium.

Electrons principal	agents in	center/initiation
	where they	create radiation
	and	heavy internal states:

Side/after/behind glow ruled in many case by
heavies
photons

Thomson scattering difficult but of high value

Outlook

T P P

Thermal

Plasma

Processes

Equilibrium departure
a challenge

H T P P

High

Tech

Plasma

Processes

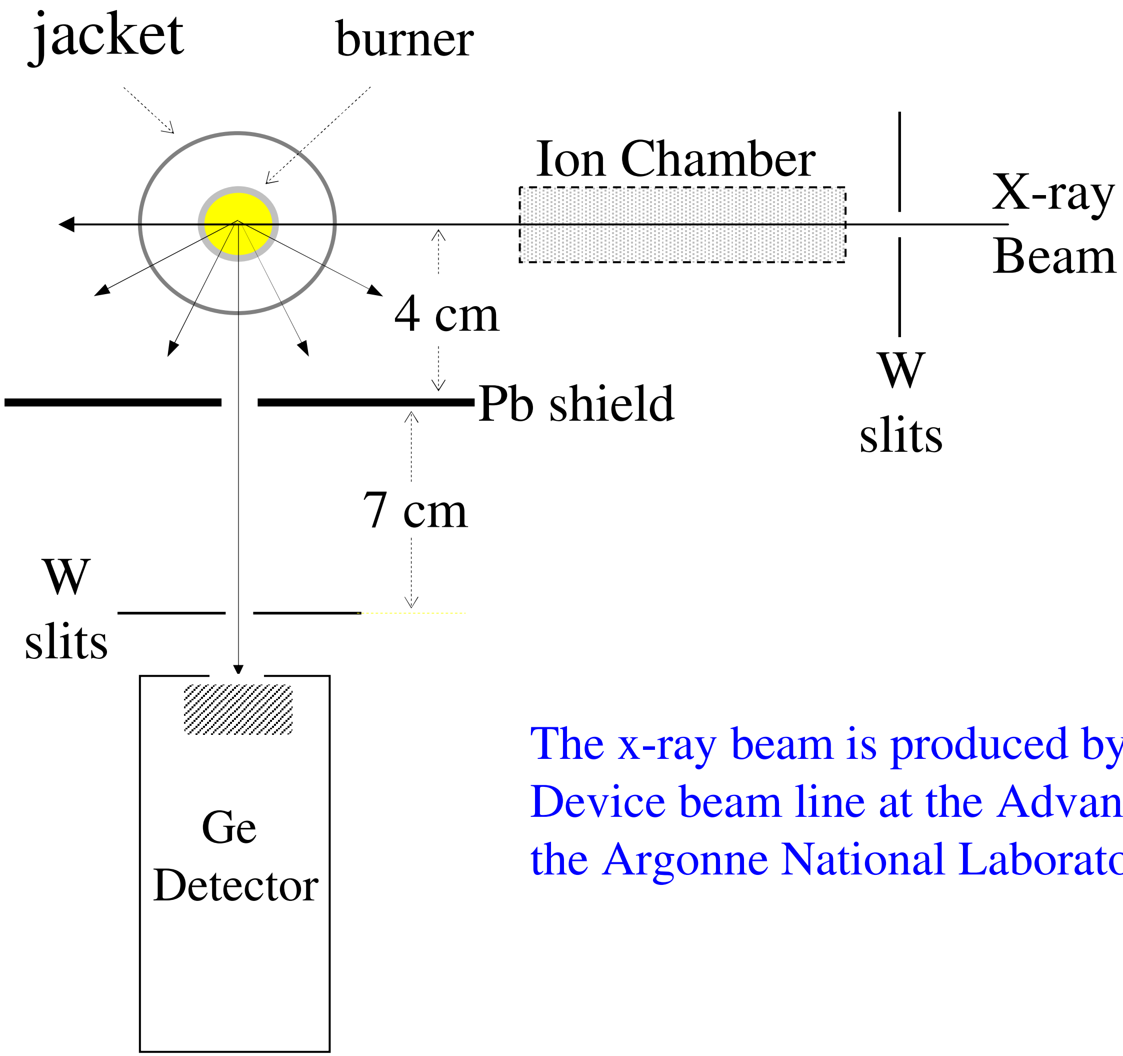
Thank you for your attention

XRF

Tanya Nimalasuriya (TU/e
Evert Ridderhof (TU/e)
John J. Curry (NIST)
Craig J. Sansonetti (NIST
Sharvjit Shastri (APS)

Advanced Photon Source
Argonne National Laboratory

XRF sketch



The x-ray beam is produced by the Sector 1 Insertion Device beam line at the Advanced Photon Source at the Argonne National Laboratory

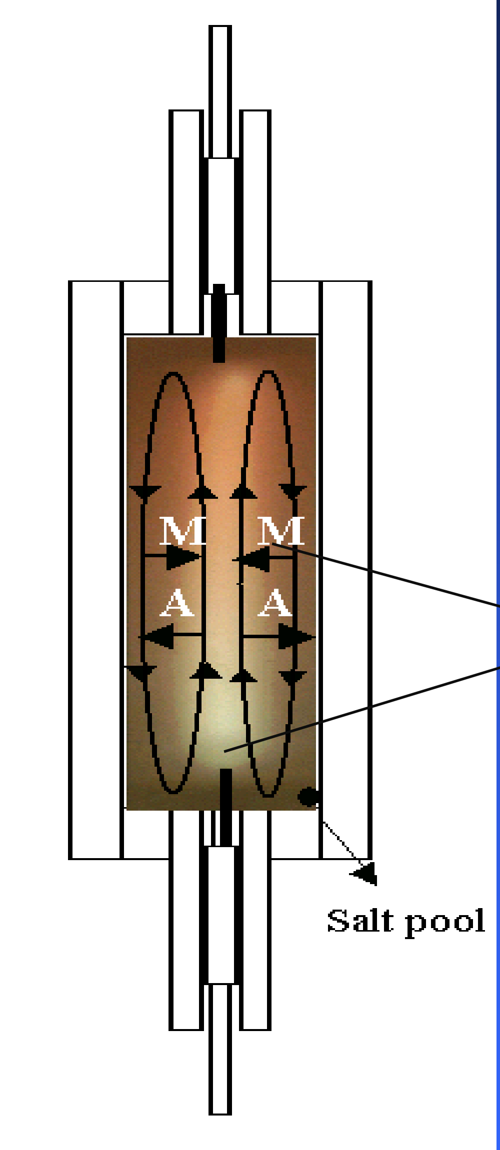
XRF advantages

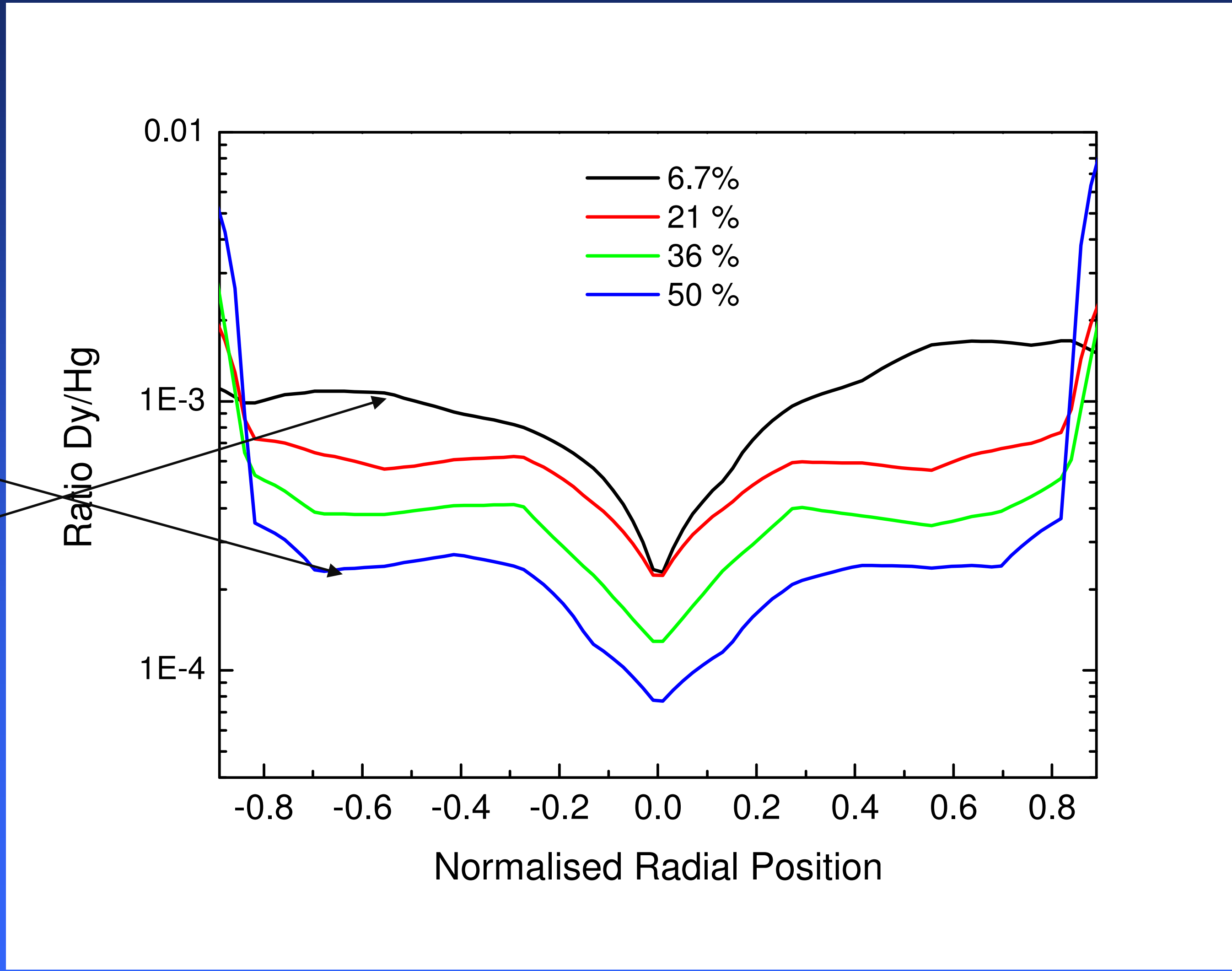
- X-ray induced fluorescence:
    - determines **elemental** densities of Dy,Hg
    - is effective anywhere in the burner

- No inversion technique is needed

- T profile with Hg densities

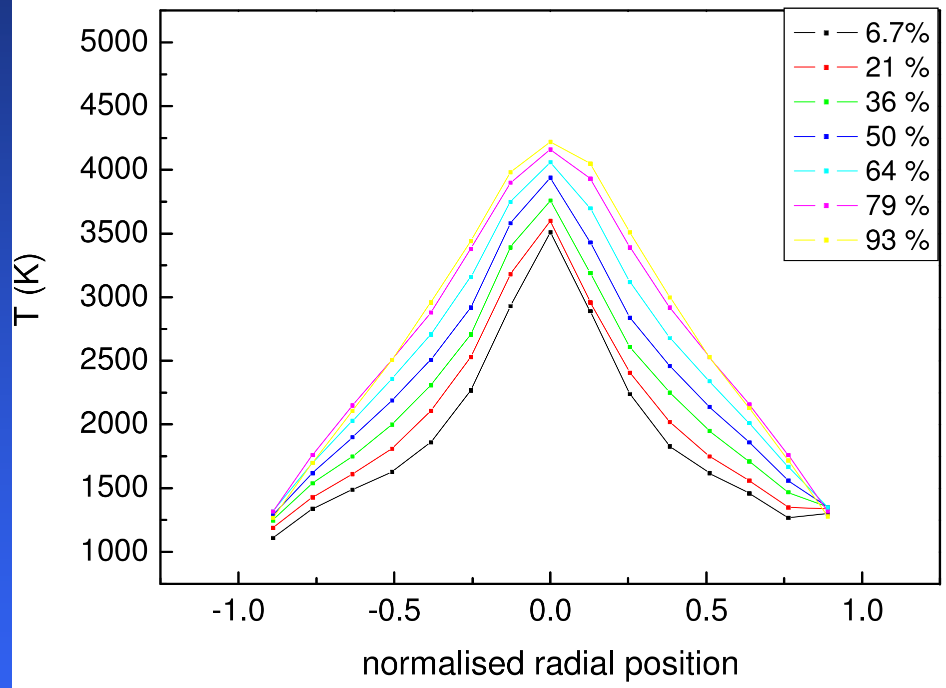
Diffusion versus (radial) convection



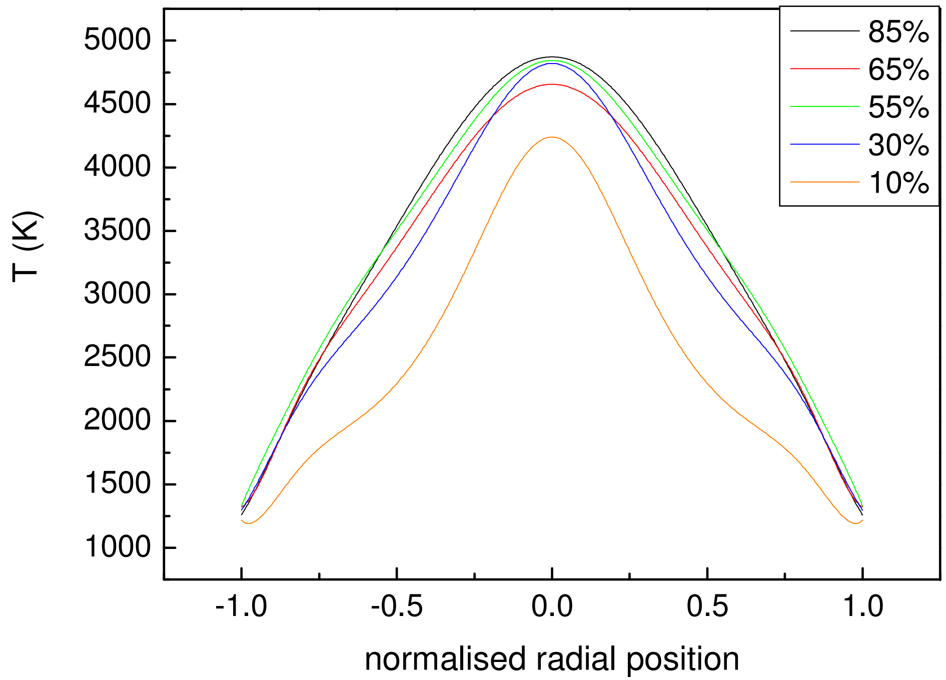


Temperature profile from Hg density

$T_{XRF} \approx T_{XRA}$ but low !!

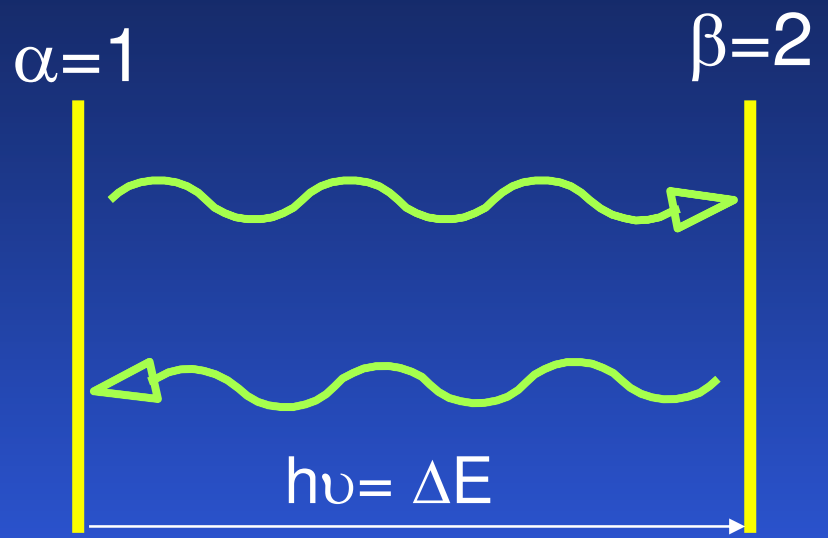


XRF 140 W



XRA 142 W, X.Y. Zhu

Example pLPE



Intense laser irradiates transition:

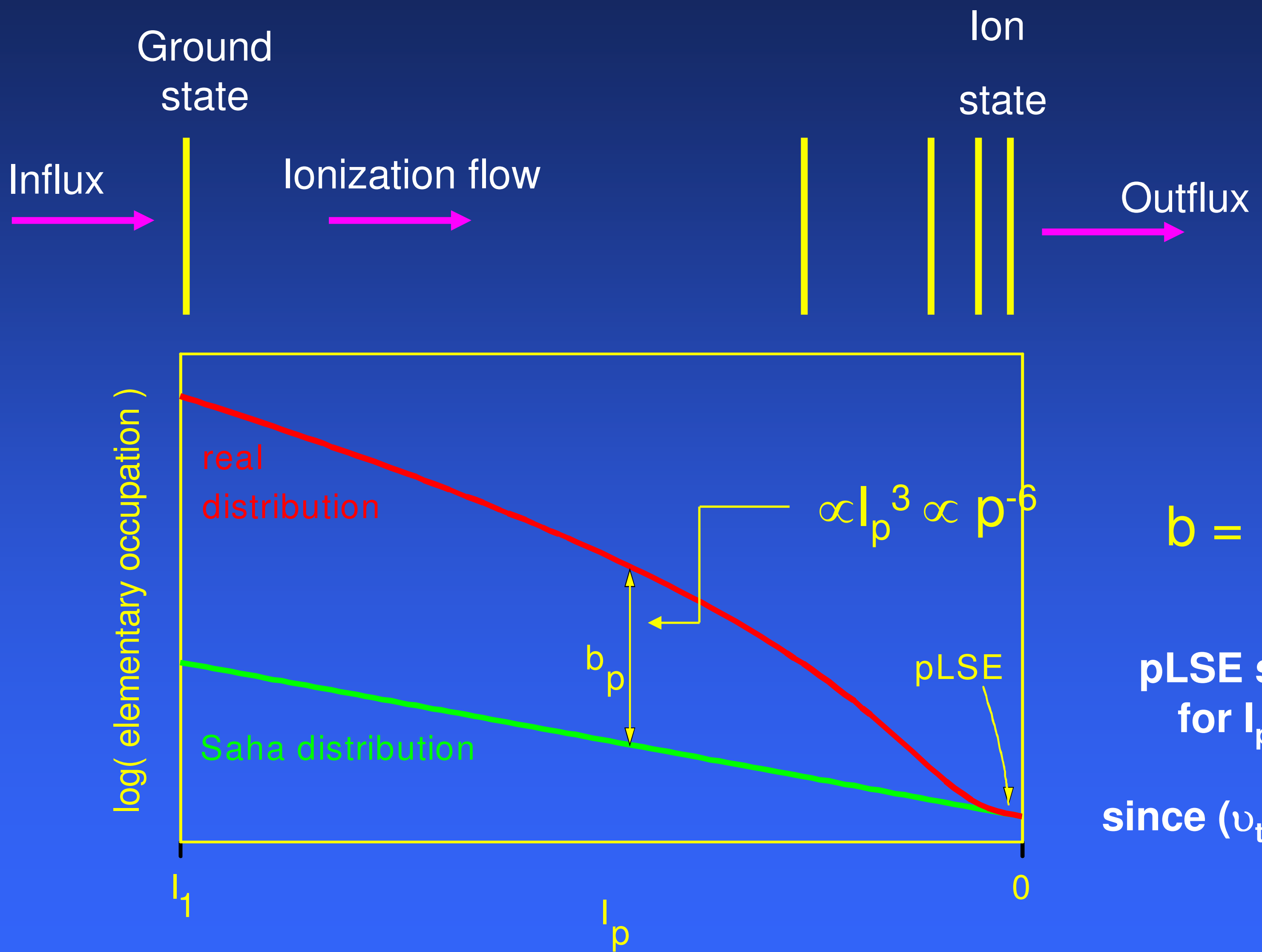
Proper balance Absorption St.Emission

Look for comparable TE situation

$T \rightarrow \infty$: $\exp -\Delta E/kT = 1 \rightarrow$ $\eta(1) = \eta(2)$

TU/e

Ion Efflux Effecting the ASDF

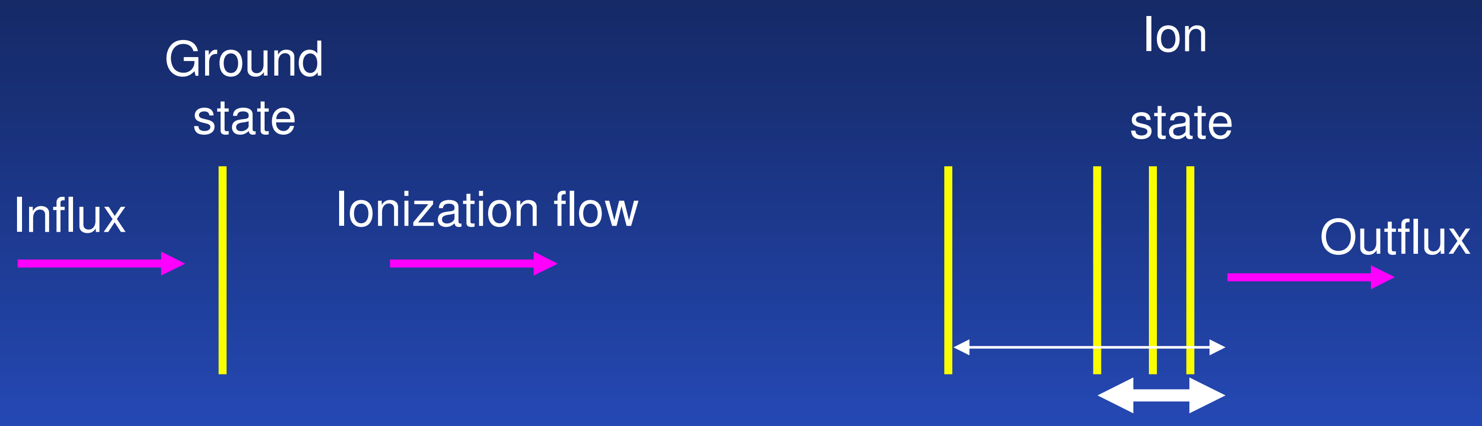


$b = n/n^s$

pLSE settles for $I_p \to 0$

since $(\upsilon_t/\upsilon_b)^S \to 0$

Example pLSE



Approaching continuum:

Equi. restoration rates increase

Look for comparable TE situation

Saha equation ruled by electrons from continuum

$$\eta^s(p) = \eta_+ \, \eta_e \, \mathcal{V}_e \exp\left(I_p/kT_e\right)$$

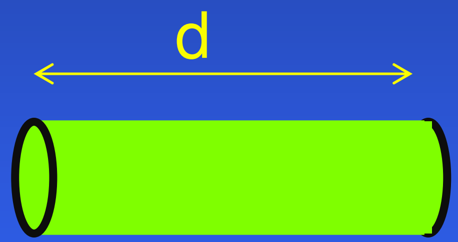
The efficiency

How many photons detected ?

Combined
Absorption
Emission

$\xi = F_{scat} \; F_{coll} \; F_{det}$

F_{scat} the scatter-fraction



$\tau = kd = n_e \sigma \, d$

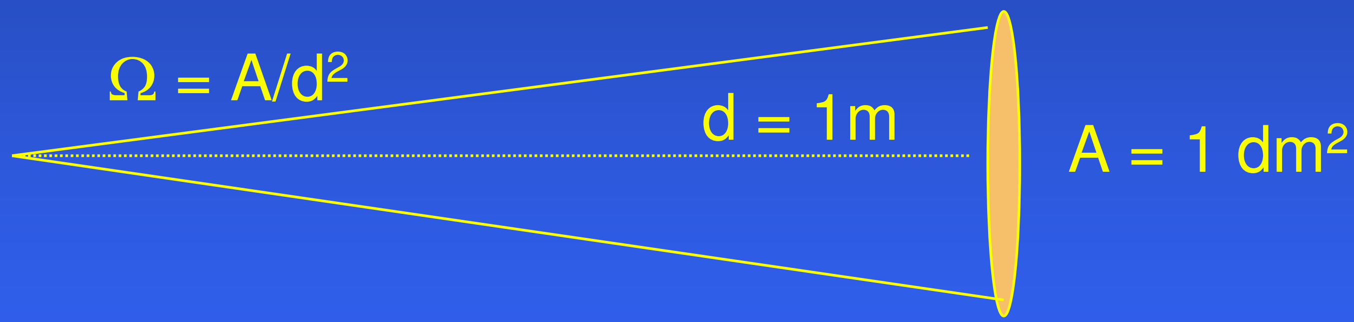
Take :

$\sigma = 6.65 \; 10^{-29} \; m^2$
$n_e = 10^{20} m^{-3}$
$L = 1 \text{ cm} = 10^{-2}$

$\rightarrow \tau = 10^{-10}$

The collected fraction

The collected fraction: possible 1 dm^2 lens at 1 m



$\Omega = A/d^2 = 10^{-2}sr$

Solid angle fraction $\chi = \Omega/(4\pi) = 10^{-3}$

$\rightarrow F_{coll} = 10^{-3}$

The detected fraction

The detection fraction $F_{det} = 10^{-2}$

$\xi = F_{scat} \; F_{coll} \; F_{det} = \quad 10^{-10} \, 10^{-3} \, 10^{-2} = 10^{-15}$!!!

Laser needed e.g. 1 mJ $\approx 5 \; 10^{15}$ photons.

Several TS competitors

- Collectivity
- Rayleigh scattering
- False stray light, vessels
- Plasma photons
- Laser produced plasma

The competitors

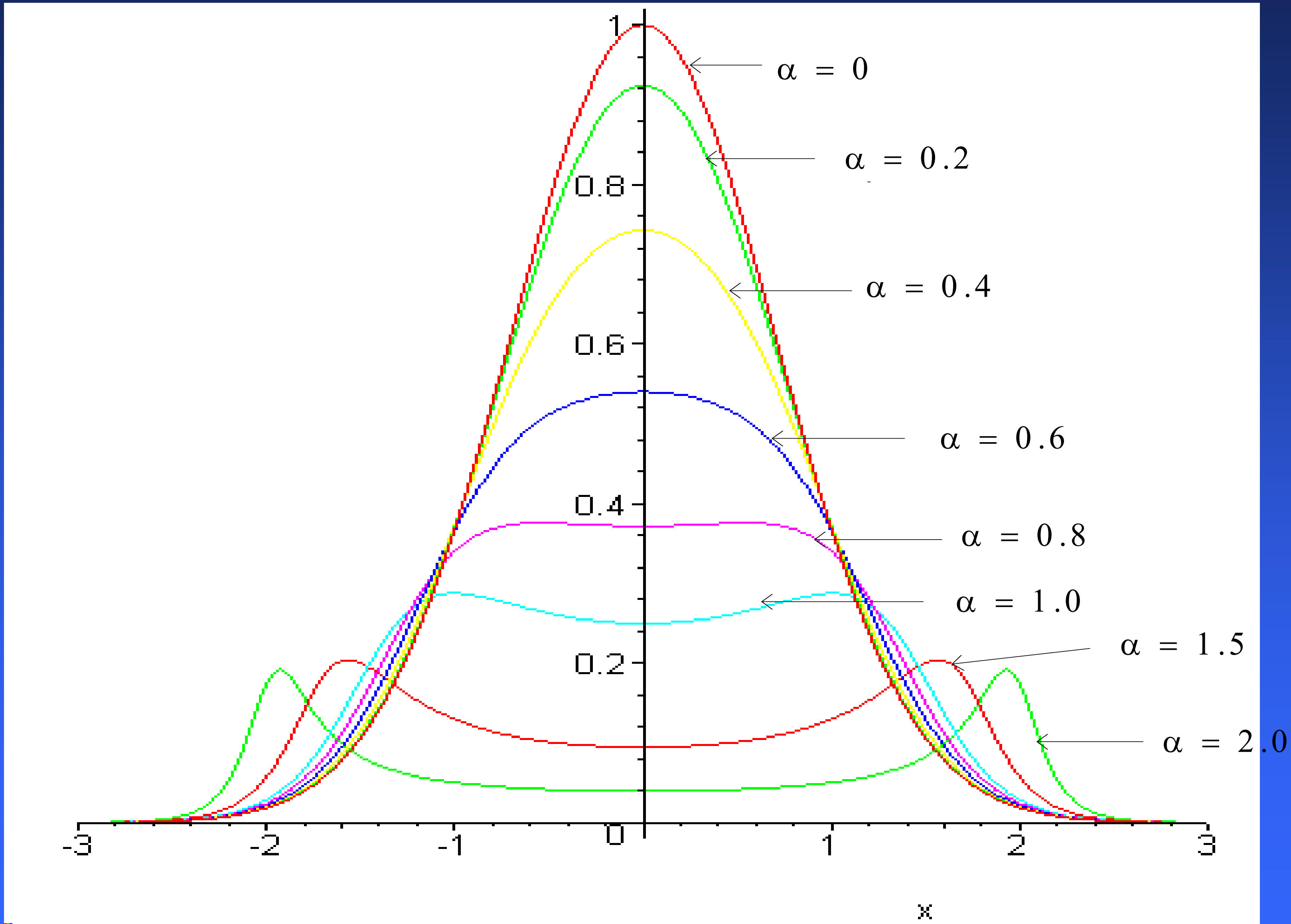
Collectivity	Change of Gaussian
Rayleigh scattering	At λ_0
False stray light, vessels	At λ_o
Plasma photons	At λ_o and in $\Delta \lambda$ - TS
Laser produced plasma	A different plasma

The competitors

Collectivity	**Change of Gaussian**
Rayleigh scattering	At λ_0
False stray light, vessels	At λ_o
Plasma photons	At λ_o and in $\Delta\ \lambda$ - TS
Laser produced plasma	A different plasma

TU/e

TS spectra shapes for collective behavior



The competitors

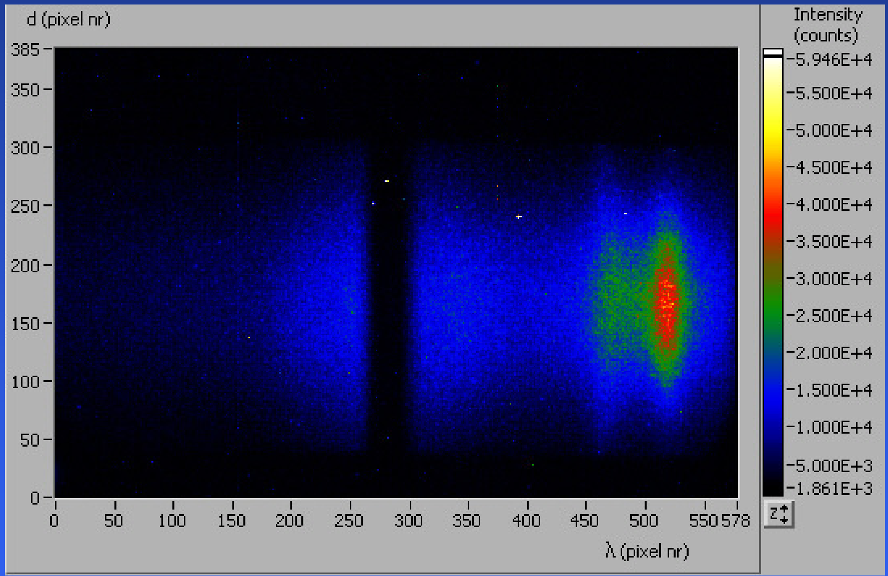
Collectivity — Change of Gaussian

Rayleigh scattering — **At λ_0**
False stray light, vessels — **At λ_o**

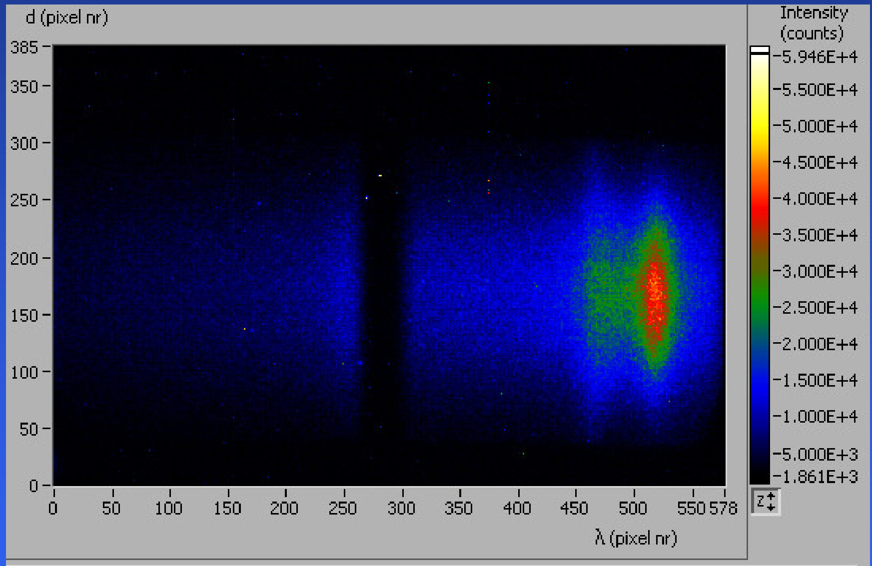
Plasma photons — At λ_o and in $\Delta\lambda$ - TS
Laser produced plasma — A different plasma

Plasma Background Light 1

Thomson + Plasma



Plasma Background

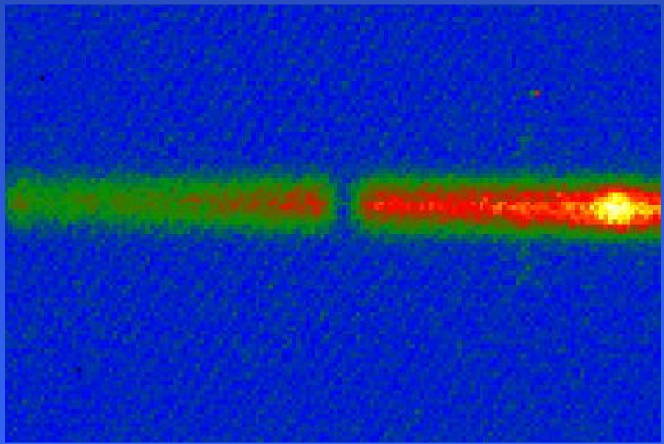


The competitors

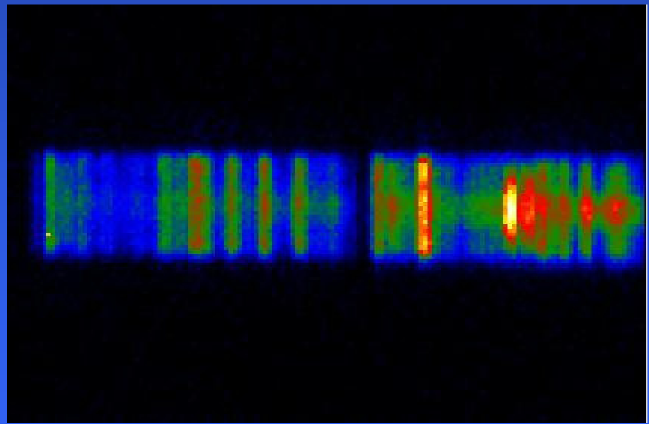
Collectivity	Change of Gaussian
Rayleigh scattering False stray light, vessels	At λ_0 At λ_o
Plasma photons Laser produced plasma	**At λ_o and in $\Delta\lambda$ - TS** A different plasma

Plasma Background Light 2

150W Hg lamp



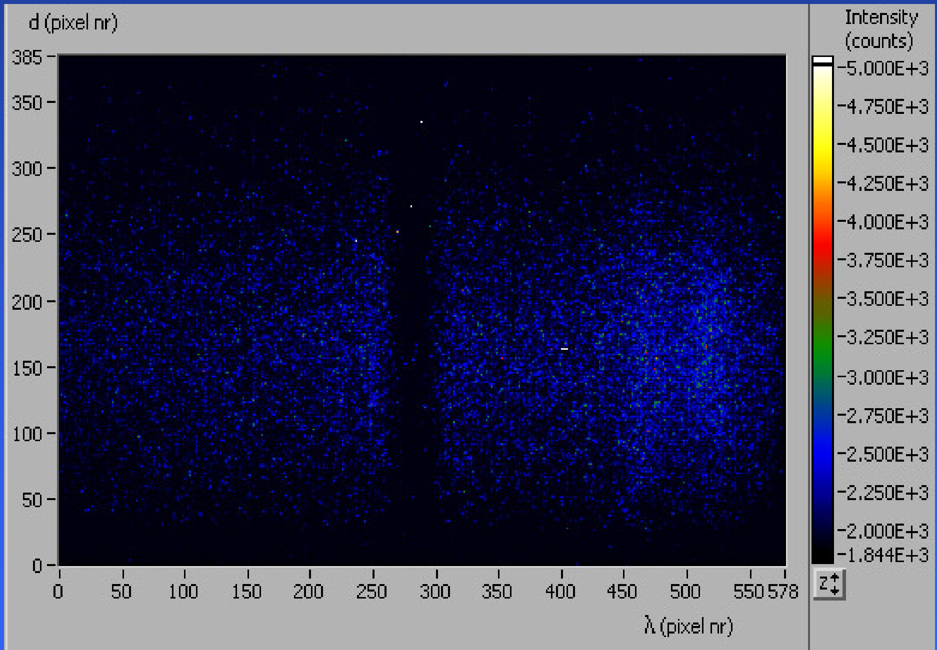
150W Hg+CeI_3 lamp



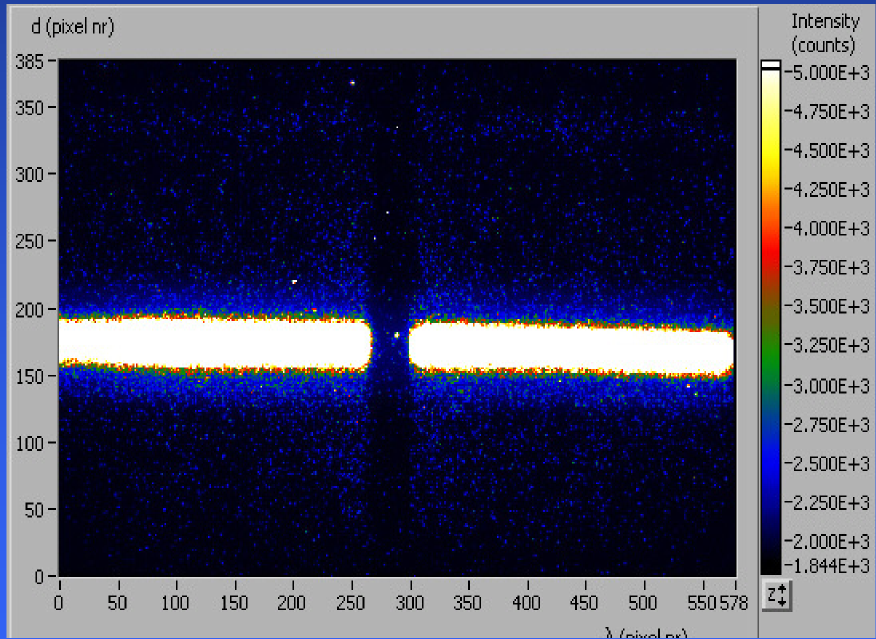
TU/e

Laser Produced Plasma

Laser power: 4mJ. Focal length:15cm.



Lamp_background_60s



TS_60s

The competitors

Collectivity	Change of Gaussian
Rayleigh scattering False stray light, vessels	At λ_0 At λ_o
Plasma photons Laser produced plasma	**At λ_o and in $\Delta\lambda$ - TS** A different plasma

Solution Plasma light

Avoid LPP: Pulse energy < 1 mJ: **no extra plasma**

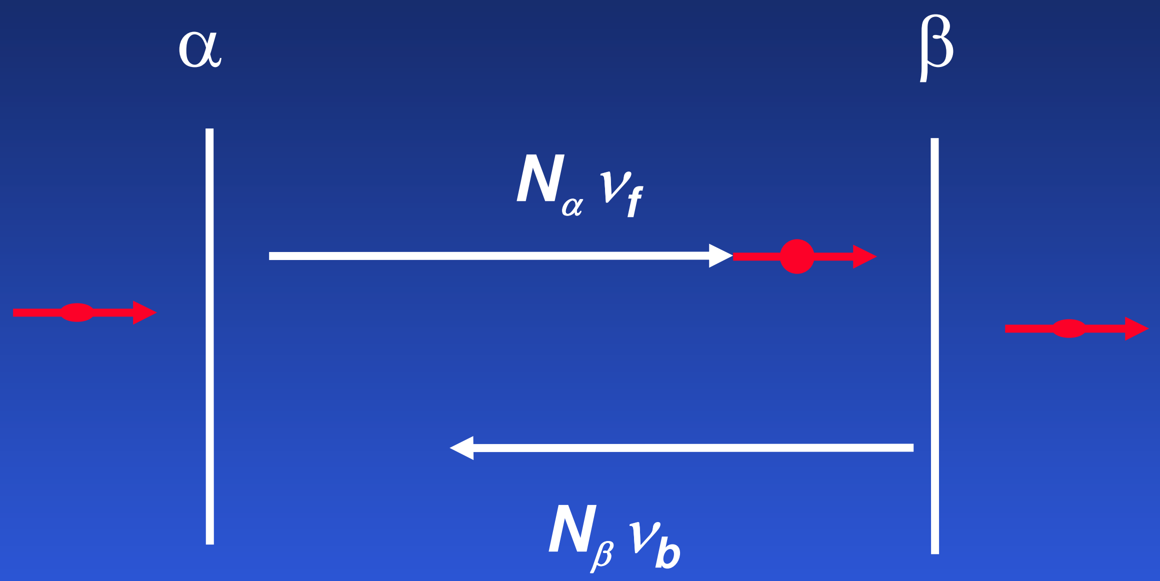
Compress laser pulse period

Method employed by Erik Kieft ASML

Using the Ekspla $\tau < 0.2$ ns !!

Instead of “normal” $\tau < 8$ ns

Equilibrium Departure



Non-Equilibrium $\quad N_\alpha \nu_f = N_\beta \nu_b + N_\beta \nu_t$

Equilibrium $\quad N_\alpha^{eq} \nu_f = N_\beta^{eq} \nu_b$

$y = N/N^{eq}$

$y(\alpha) = y(\beta)[1 + \upsilon_t \tau_b]$