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Fraunhofer Institut Lasertechnik ILT

Plasma and Radiation Modelling of EUV Sources for Micro Lithography

Thomas Krücken

ICAMDATA05, Meudon, France
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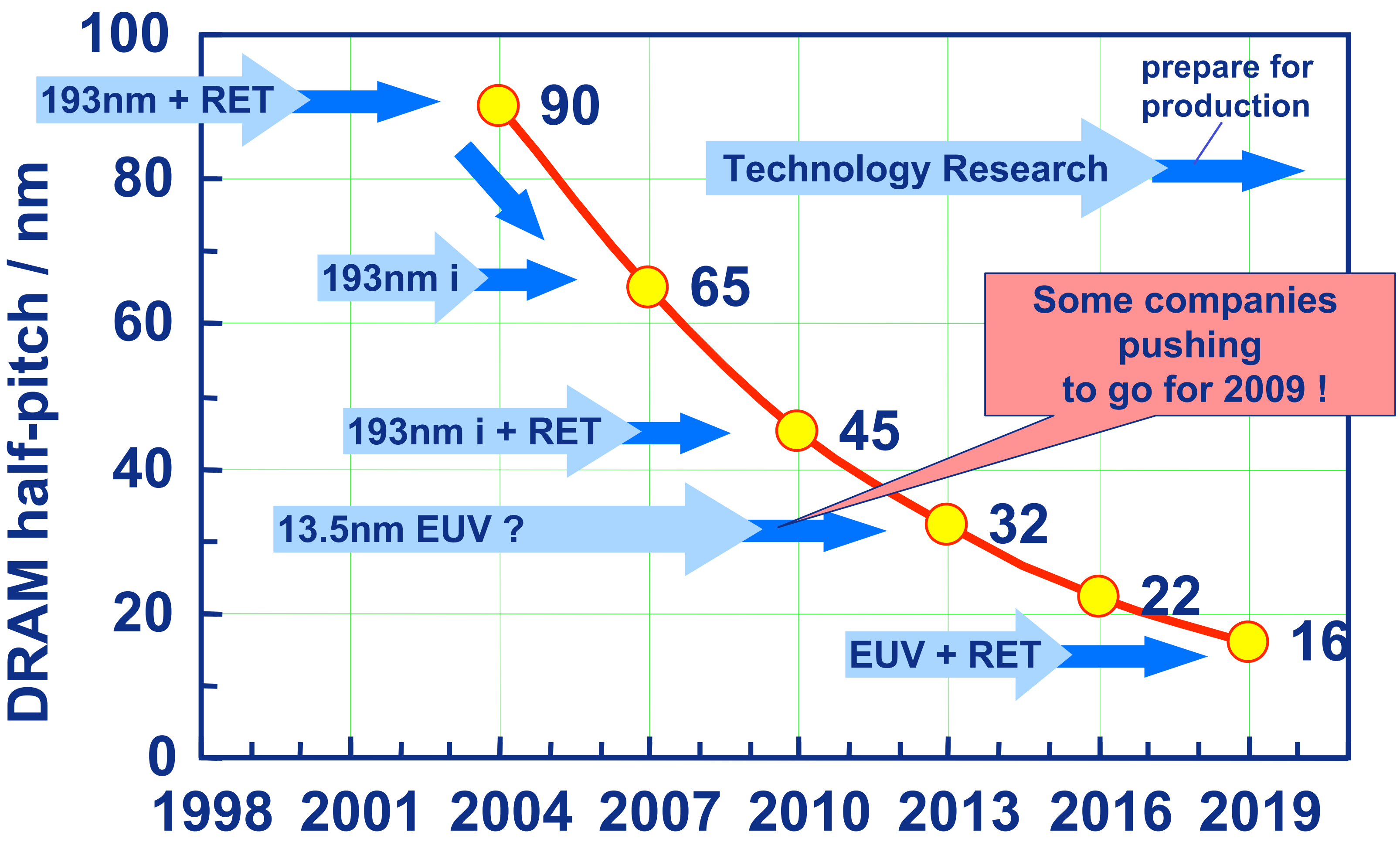
Contents

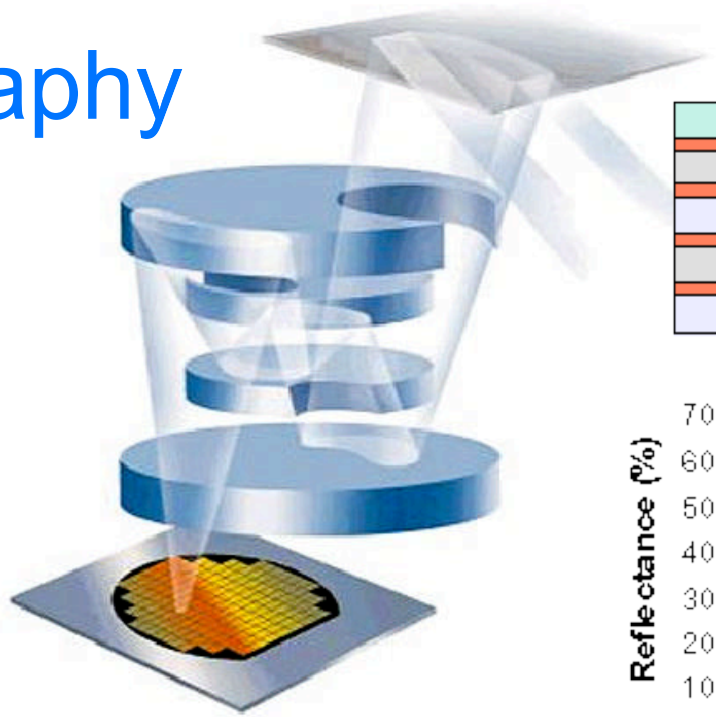
- Requirements of EUV Micro Lithography
- Atomic theory and EUV Radiators
  - Xenon as EUV Radiator
- Very simple plasma model of Xe Pinch Discharge
- Next generation EUV sources, based on Tin
  - Tin as EUV Radiator
  - EUV Source concept
- Current status of EUV Micro Lithography

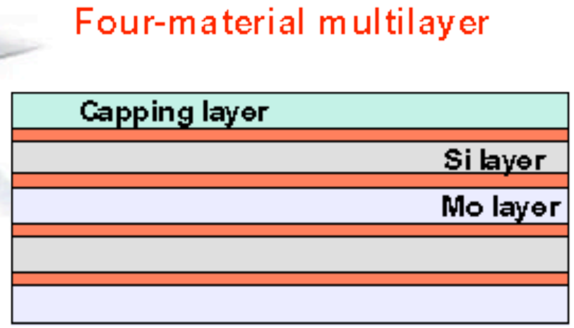
Semiconductor Roadmap 2003



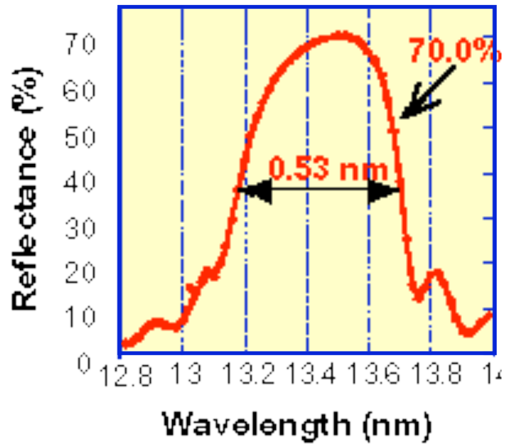
i: Immersion Technology ; RET: Resolution Enhancement Techn

EUV Lithography

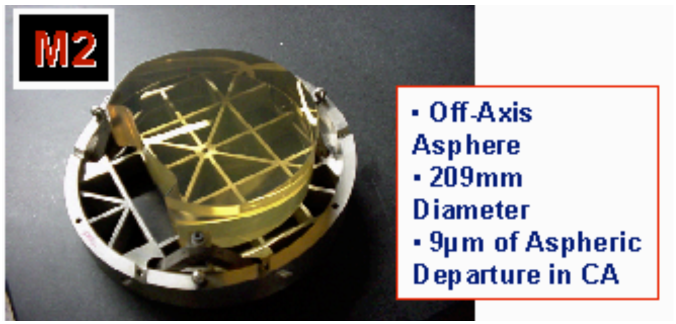




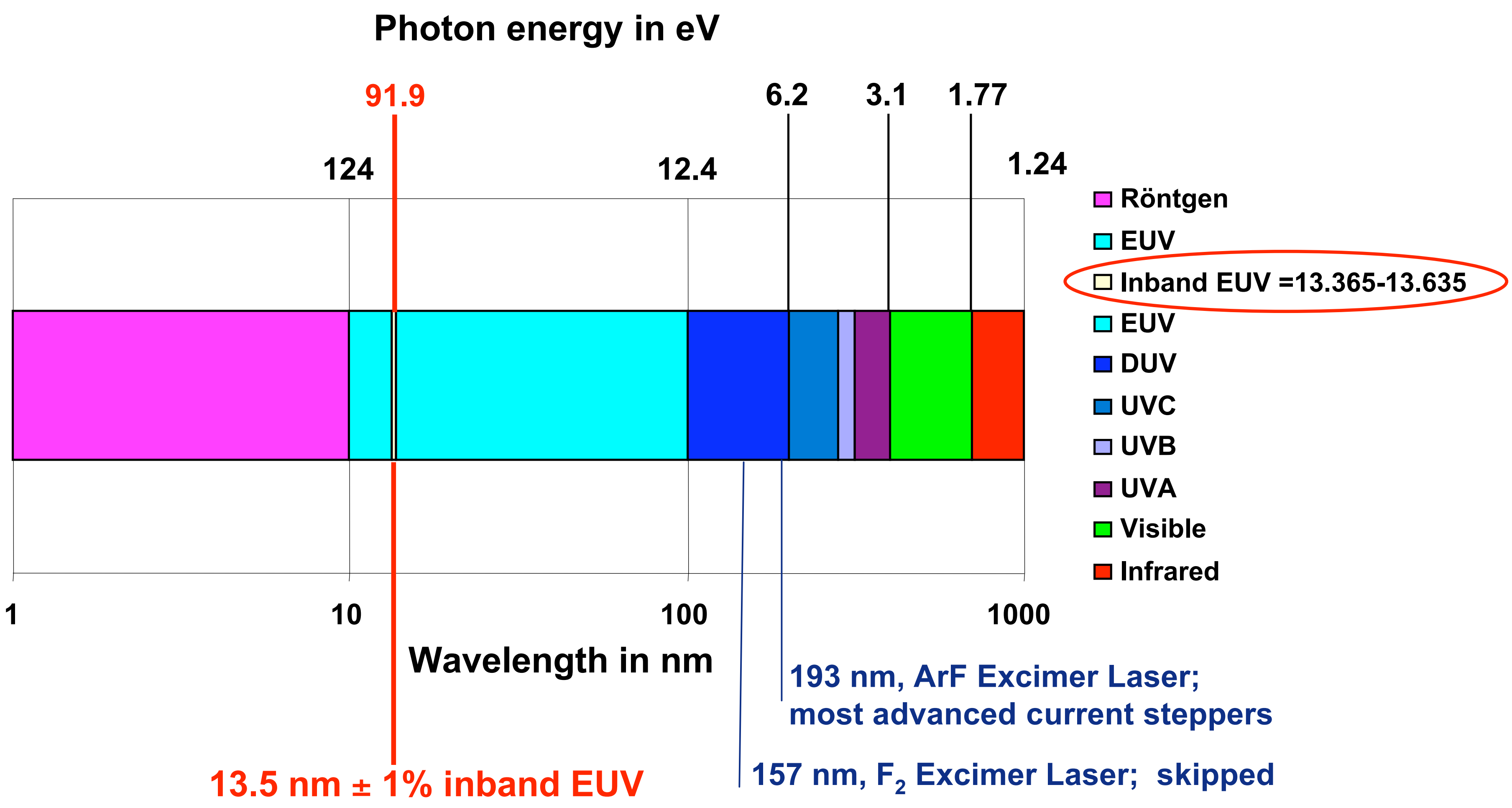
- **Vacuum system**
- **Mirror optics**
  - Grazing incidence
  - Normal incidence
- **Multilayer mirrors available !**
  - for 13.5 nm wavelength
  - bandwidth only ~ 0.5 nm
- **Extreme sub-Nanometer requirements**
  - precision of optical surfaces
  - low (zero) thermal expansion



First EUV optics completed



EUV wavelength and Photon energy range



Conversion Efficacy = CE = inband EUV radiation in 2π / input pov

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Periodic table of elements, electron configurations

radial quantum number = 1, 2, 3, 4, 5, 6 …

angular momentum quantum number = s, p, d, f, g, ...

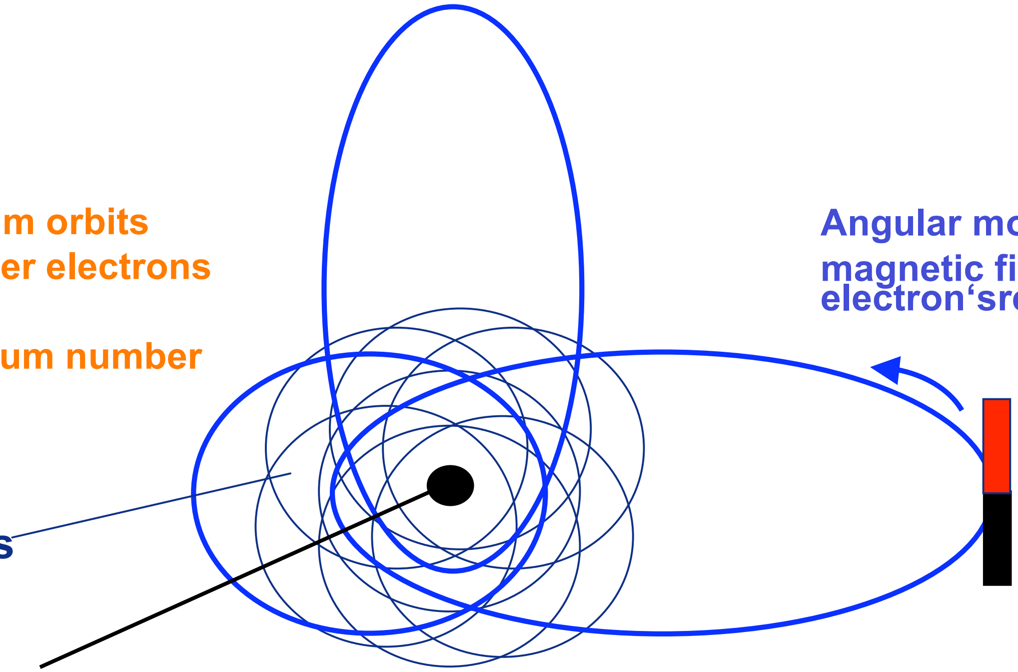
max. number of electrons in shell = 2, 6, 10, 14, 18,

1s2
2s2 2p6
3s2 3p6 3d10
4s2 4p6 4d10 4f14
5s2 5p6 5d10 5f14 5g18
6s2 6p6 6d10 6f14 6g18 6h24

Xe : 1s2 2s2 2p6 3s2 3p6 3d10 | 4s2 4p6 4d10 5s2 5p6
Xe^{+10}: 1s2 2s2 2p6 3s2 3p6 3d10 | 4s2 4p6 4d8

Sn : 1s2 2s2 2p6 3s2 3p6 3d10 | 4s2 4p6 4d10 5s2 5p2

Angular momentum of outer shell electrons



- Number of energy levels per configuration determined by total angular momentum conservation and Pauli principle
- Half filled outer shells with high angular momentum have many energy levels ⇒ „grass-like“ spectra

Atomic plasma physics package
ADAS,
University of Strathclyde, Glasgow

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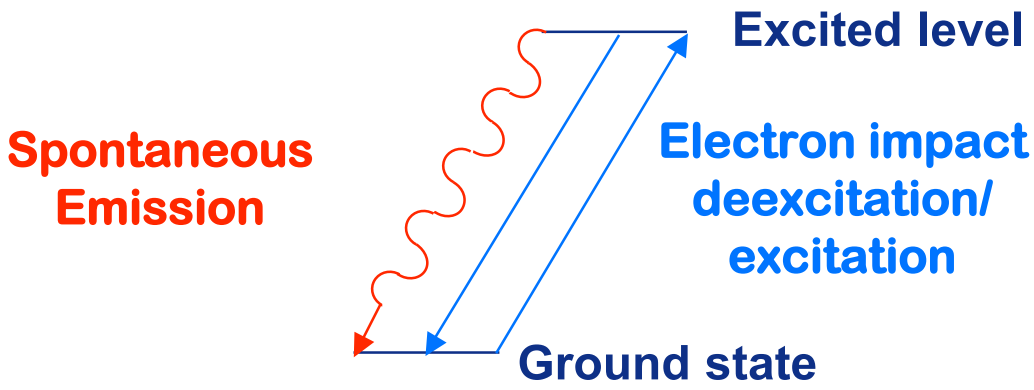
1. Step: Calculation of energy levels and transitions

- **Based on Cowan-O'Mullane Hartree-Fock atomic structure code**
- **Input: Electron Configurations, i.e. Xe^{10+}:**
  - **4s2 4p6 4d8 (ground state configuration)**
  - **4s2 4p6 4d7 4f1**
  - **4s2 4p6 4d7 5s1**
  - **4s2 4p6 4d7 5p1**
  - **4s2 4p6 4d7 5d1**
  - **4s2 4p5 4d9**
  - **Exact calculation of 4f-levels requires even more configurations**
- **Calculates energy levels incl. HFS like Spin-Orbit coupling, up to 1200 levels per ion stage, accuracy ~ 0.3 nm …**
- **Calculates photonic Transitions, i.e. A-values, between all levels for el. Dipole, mag. Dipole, up to 300000 transitions**
- **Calculates excitation/dexcitation rates by (Maxwellian) electron impact for all transitions in Born-Oppenheimer approximation**
- **Results are stored in file for further use**

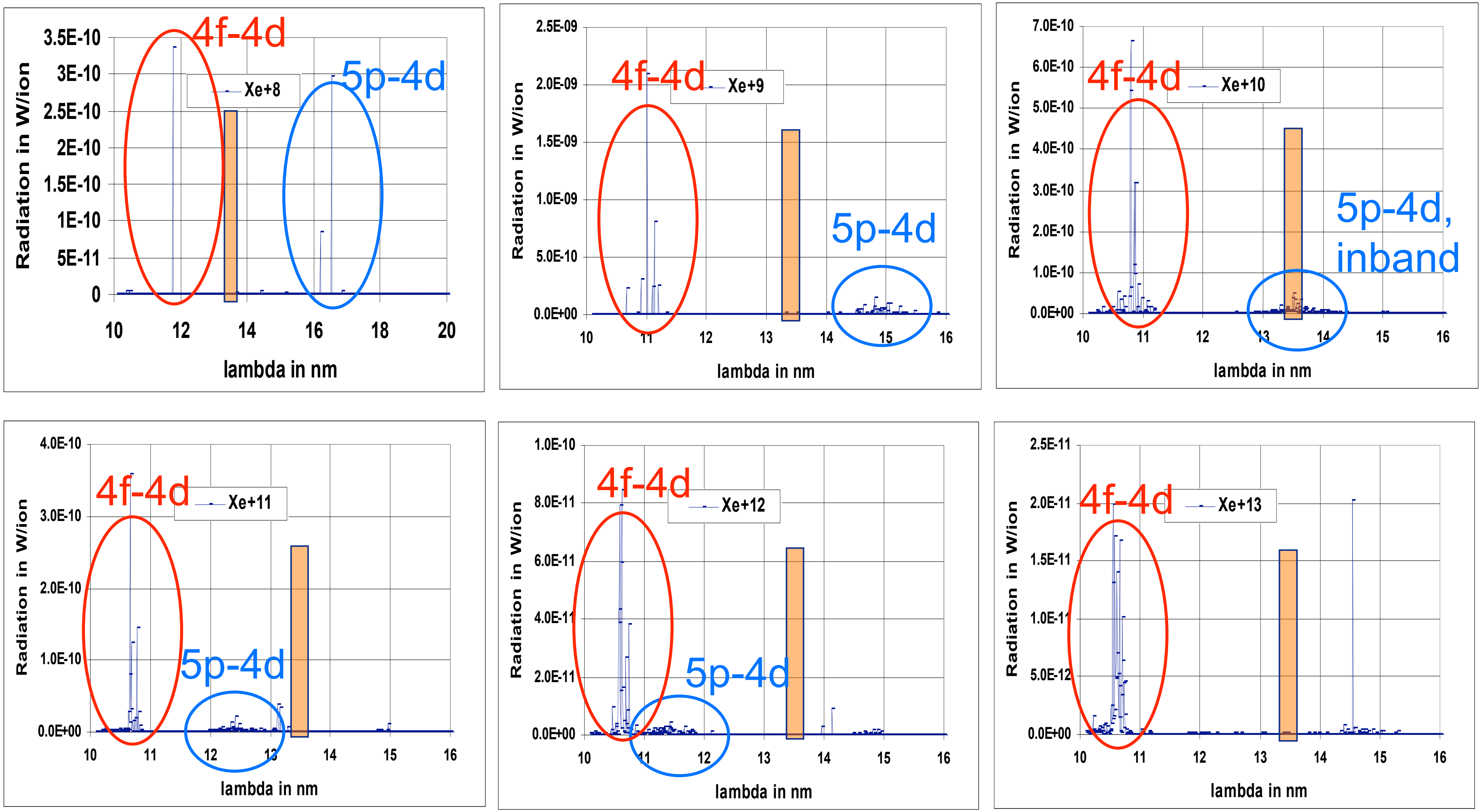
2. Step: Excited states population and spectra

- Balances all processes, i.e. calculates collisional radiative population equilibrium as function of T_e, n_e



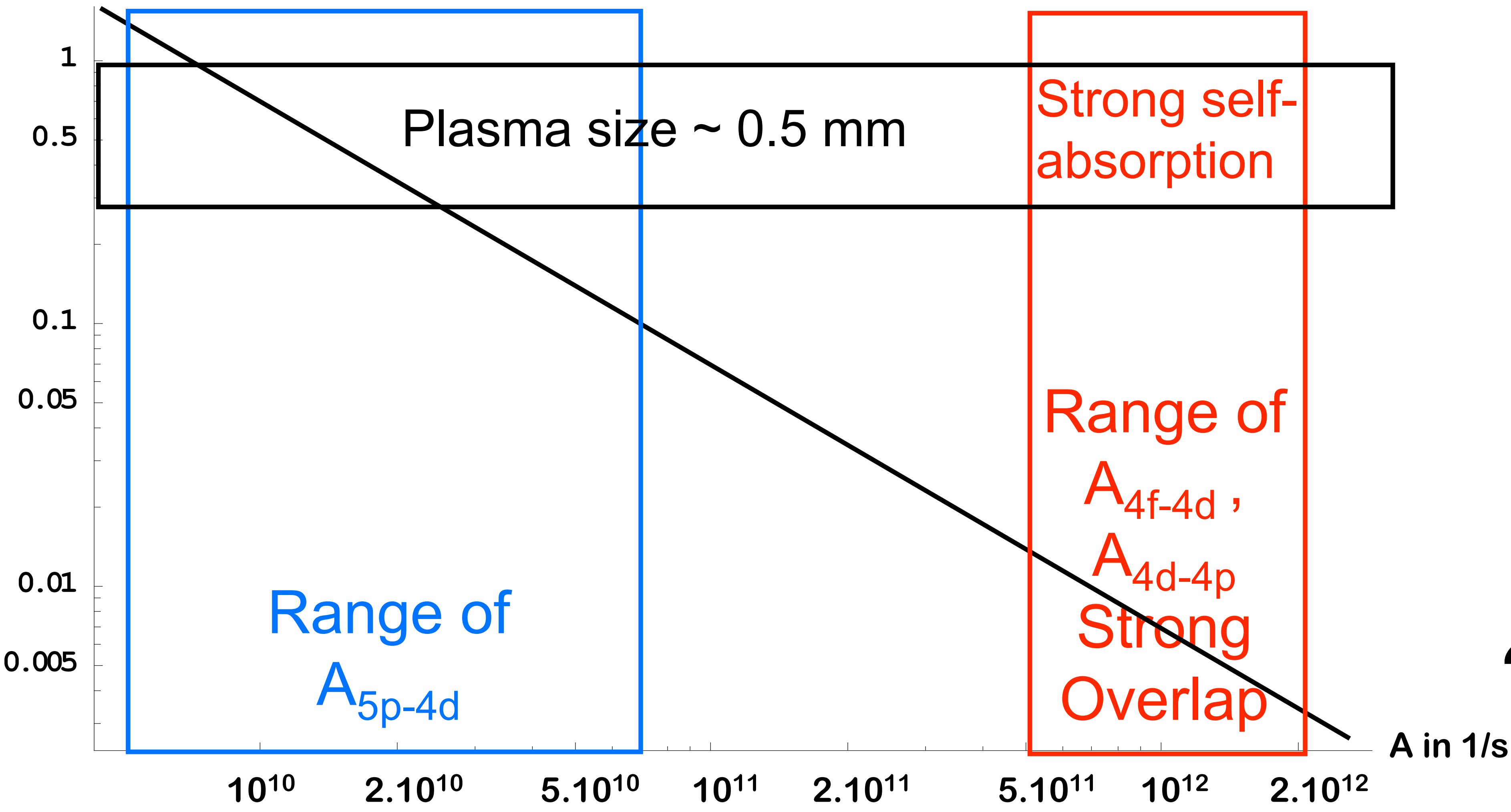
- Transition Corona / CR / LTE
- From an excited states population total radiated power and emission spectra of individual ions are calculated

Optically thin Spectra of Xe^{+8} - Xe^{+13} ions; T_e=32 eV, $n_e=10^{17}/cm^3$



Opacity / Optical Depth s, n=10^{17}/cm^3;

$$\frac{1}{s} = \frac{\lambda^4}{8\pi c} A_{21} \frac{g_2}{g_1} \frac{n}{\Delta\lambda}, \qquad \Delta\lambda = \Delta\lambda_{Doppler}(T = 1000eV) \sim 3\,pm$$



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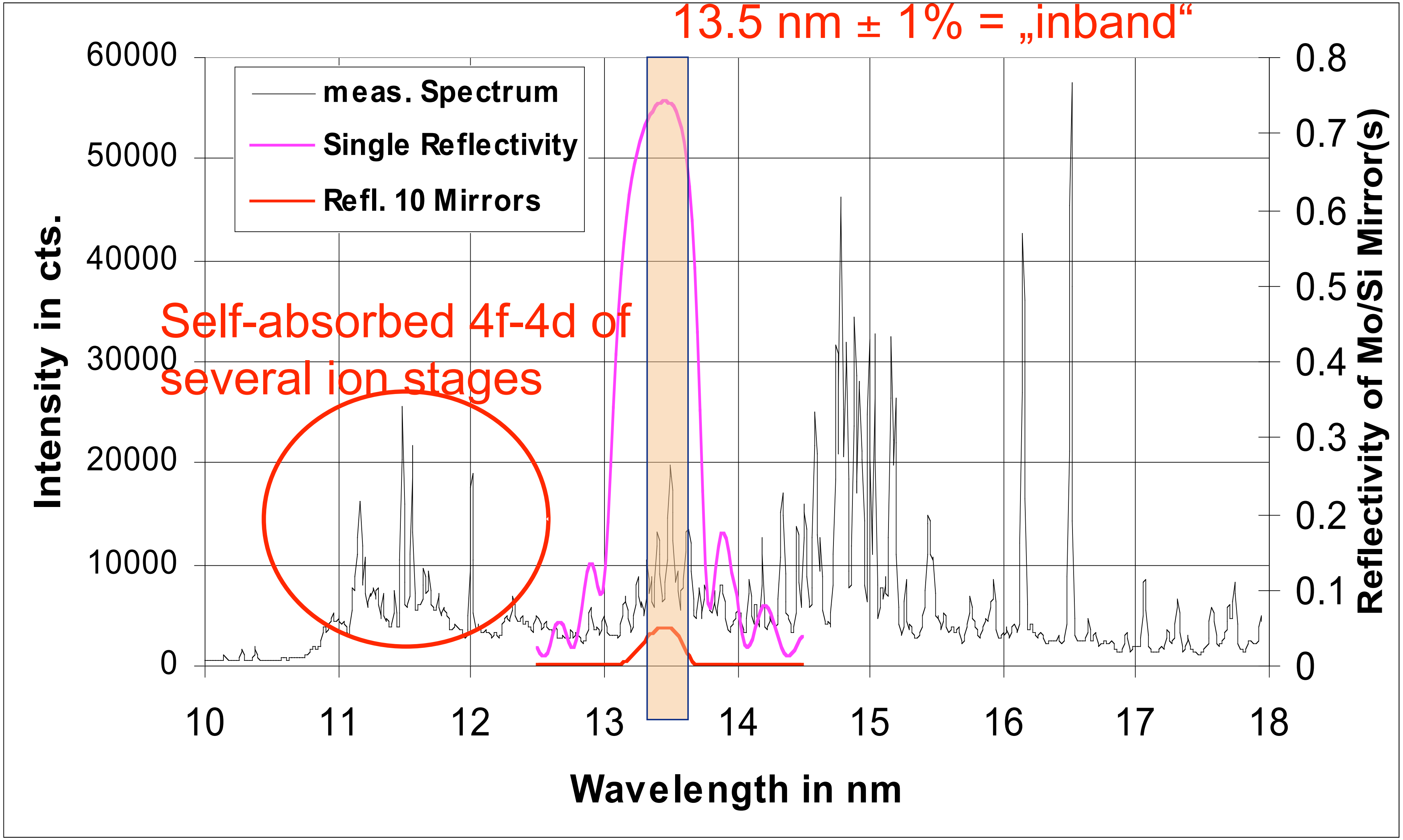
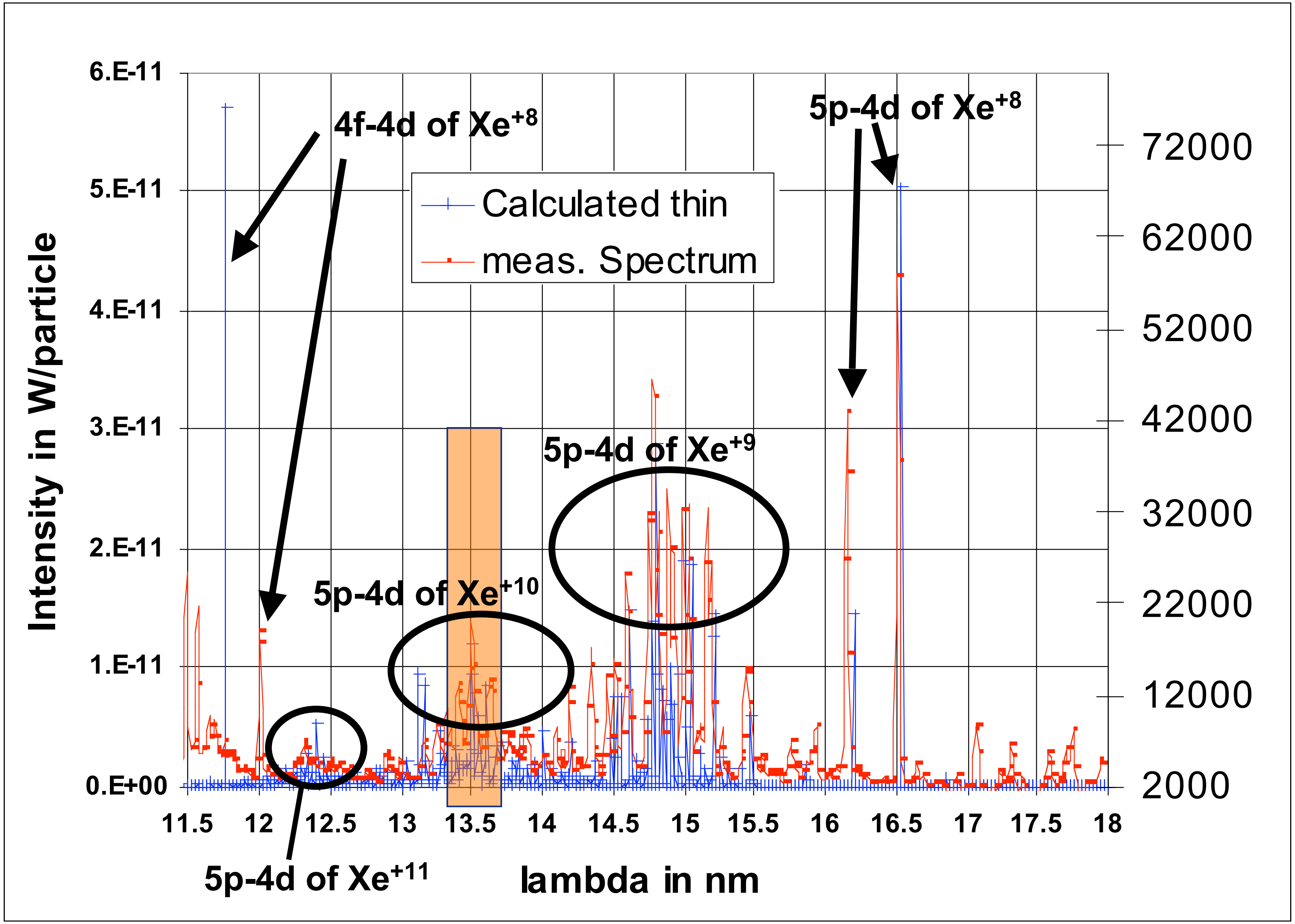
Measured EUV Spectrum of Xe



Thin Xe spectrum of ion mix near 13.5 nm



Most important Spectral properties

- 5p-4d transitions
  - Energy levels depend on ionization stage
    - Can be calculated with good accuracy
  - Some absorption of photons ⇒ escape factors reduce A-values
  - Escape factors can then be used to calculate population, spectral parts due to these transitions

- 4f-4d/4d-4p transitions
  - Large overlaps of wavefunctions for higher ionization stages >+4:
  - Then: Little dependence of levels on ionization stage
    - Exact calculation of energy levels requires inclusion of many configurations
  - High angular momentum ⇒ many levels/transitions for half-filled outer shells
  - Large A-values ⇒ strong self absorption

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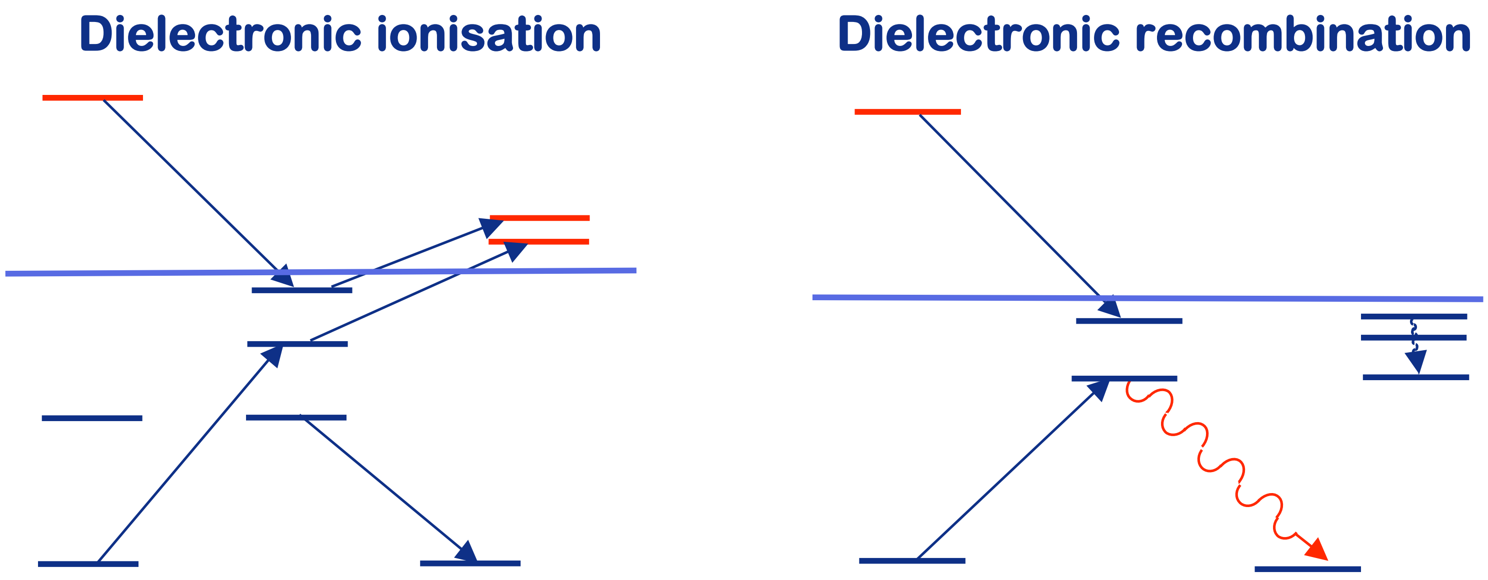
Ionisation / Recombination

- Most difficult, current subject of research
  - influence of metastables, typically other spin-system,
  - dielectronic processes very important
  - depend on many intermediate states with high n
  - influence of inner shell electrons



- ADAS evaluates effective ionisation coefficients
- complicated advanced calculations to obtain higher accuracy (< 50 %)

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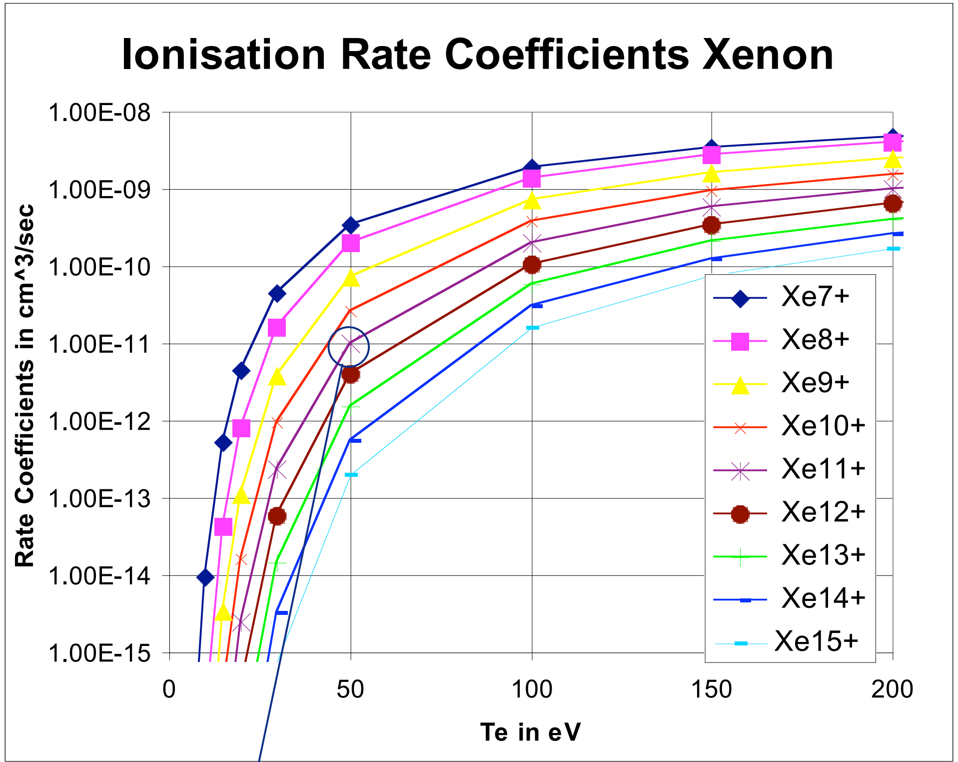
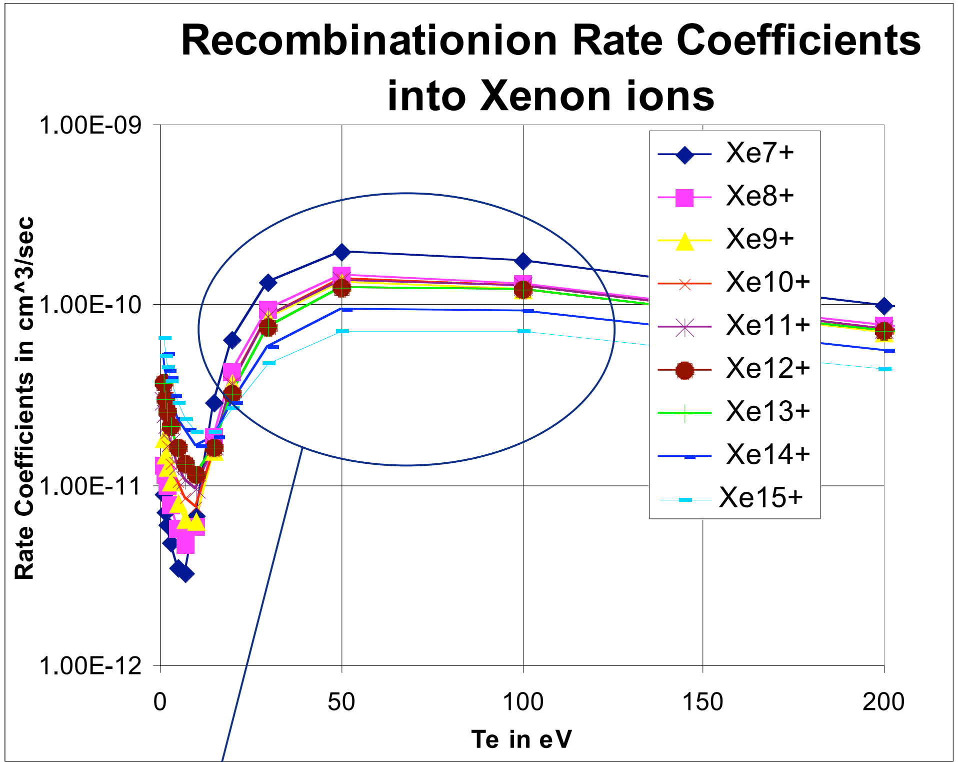
Ionisation/recombination rates of Xe-ions from ADAS





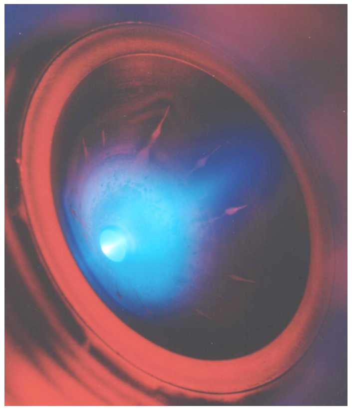
For $n_e = 10^{18}$, $T_e = 50$ eV:
$\tau_{ion} \sim 100$ ns

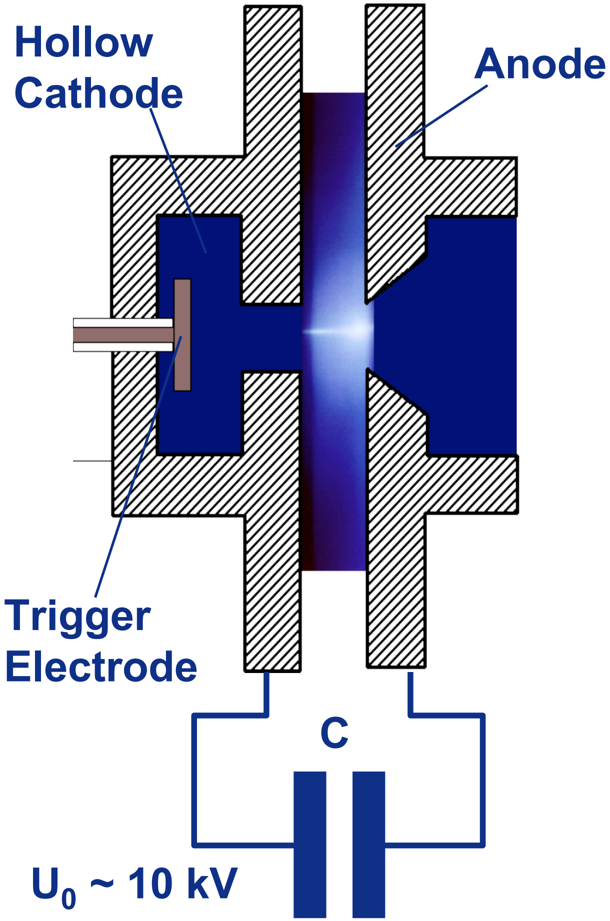
Dielectronic contributions

Philips Extreme UV: HCT Pinch as source

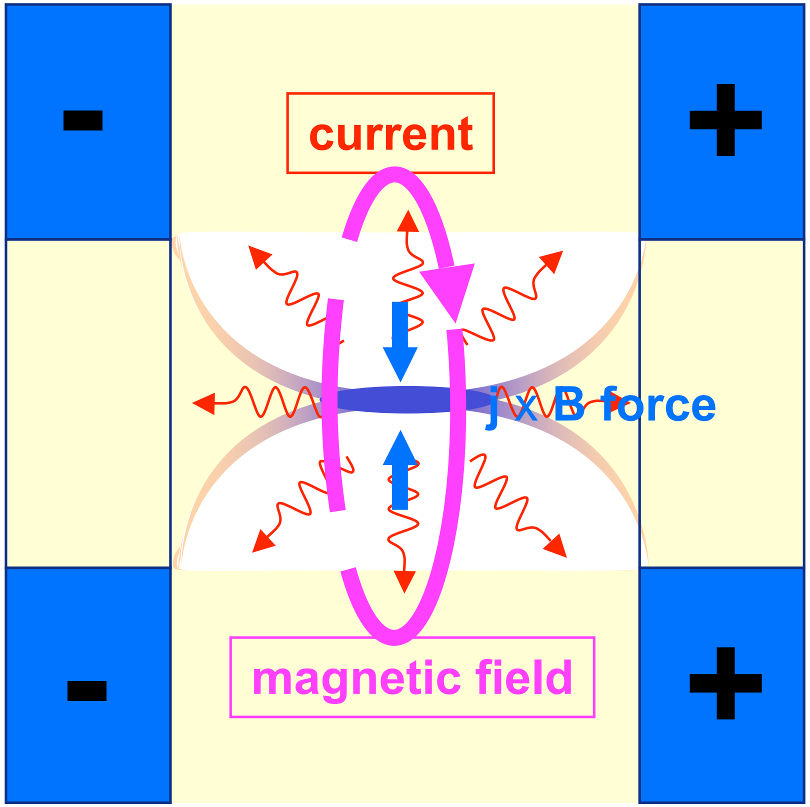
"Hollow Cathode Triggered Pinch"

- **Hollow Cathode**
  - **defined ignition & triggering**
  - **cold pressure ~ 10 Pa**
- **High current pinch discharge**
  - **"pseudo spark discharge"**
  - **production of hot plasma by magnetic (self-)compression**
  - **intense EUV radiation**





Pinch Phase after ignition

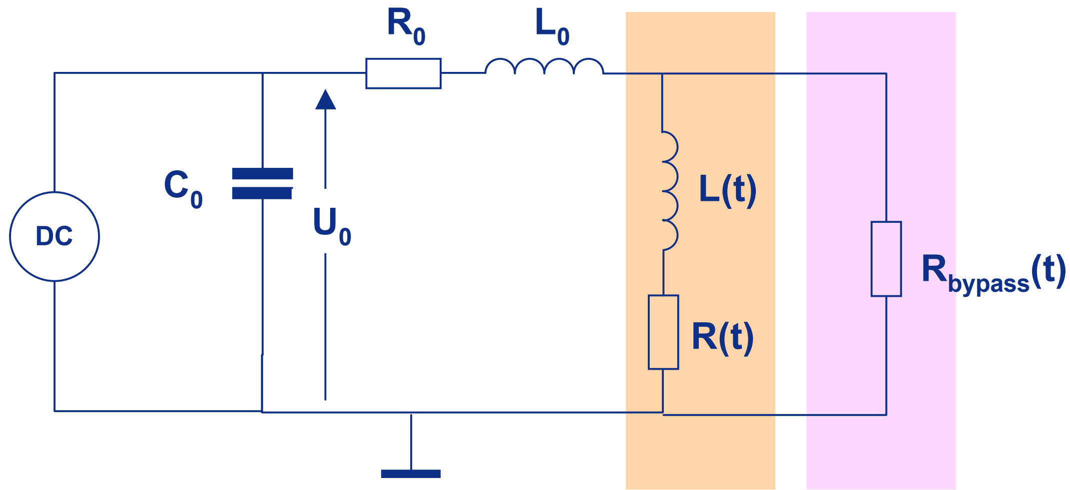


- **Magnetic compression (pinching) of Xe plasma**
- **Current several kA during pinch phase**
- **Pinch time ~ 100ns**
- **T_e ~ 50eV, n_e~10^{18}/cm^3**

Implosion times and current characteristics must be matched
⇒ Current maximum during minimum plasma radius

Electrical circuit

circuit equations, *L_0, R_0, C_0*, coupled to
pinch with *L(t), R(t)* ; Bypass with *$R_{bypass}(t)$*



Total Energy per pulse:

$$E = \frac{1}{2} C_0 U_0^{\ 2}$$

$$\frac{dU_0}{dt} = -I_{tot} / C_0$$

$$U_0 = L_0 \frac{dI_{tot}}{dt} + R_0 I_{tot} + L \frac{dI}{dt} + \left(R + \frac{dL}{dt} \right) \cdot I$$

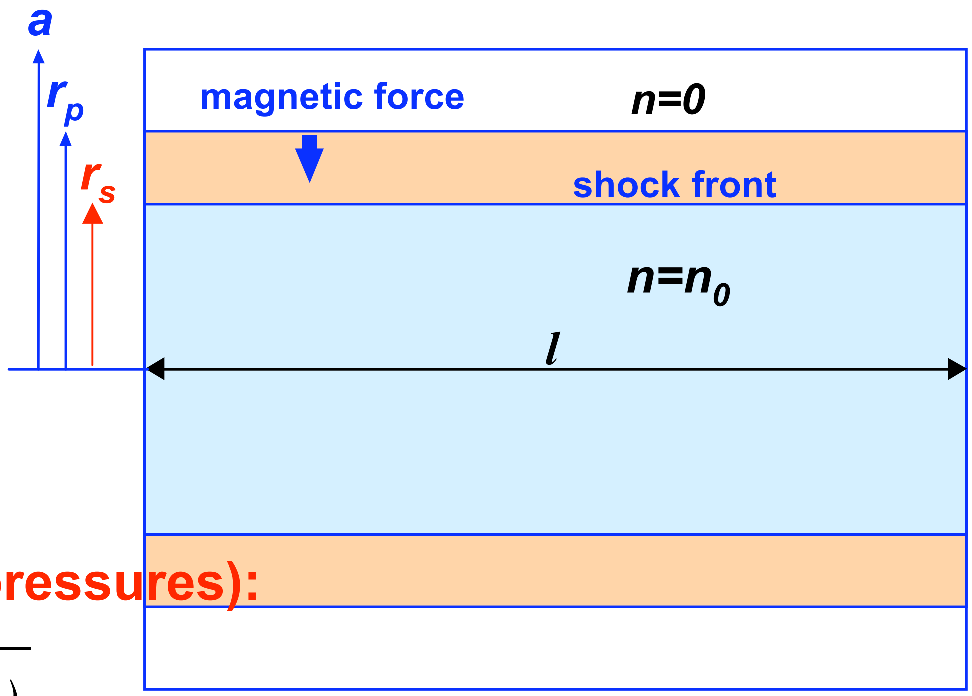
$$\tau_{Period} \sim 2\pi \sqrt{L_0 C_0}$$

$$R_{Bypass} (I_{tot} - I) = L \frac{dI}{dt} + \left(R + \frac{dL}{dt} \right) \cdot I$$

Simple Zero Dimensional Dynamic Pinch Model

Supersonic implosion phase, snowplough with shock front preceding magnetic piston,
No radial or axial profiles;
Momentum equation, piston radius r_p, starting at a:

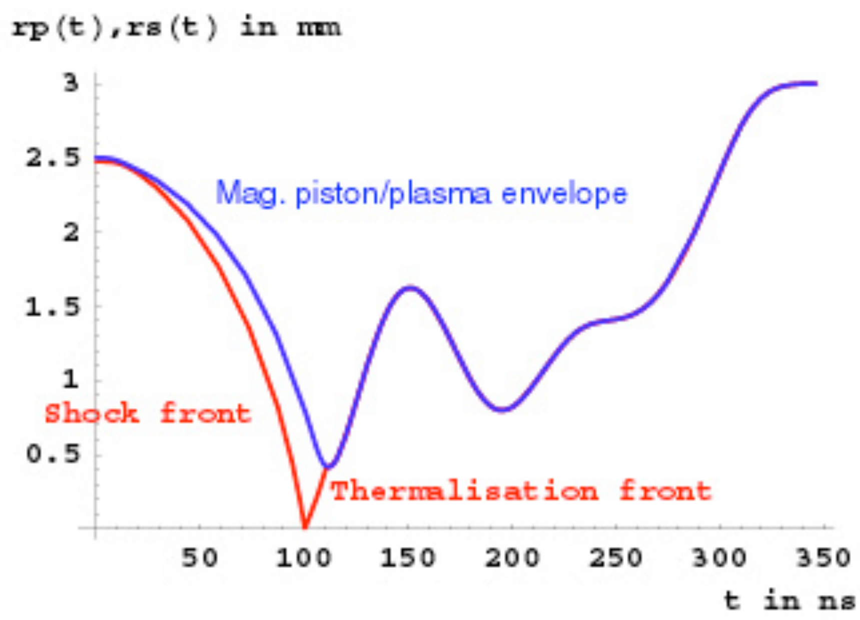
$$N\frac{d}{dt}\left(M_{atom}\left(1-{r_s}^2/a^2\right)v_p\right)=$$
$$2\pi l r_p \cdot \left(p_{therm}-p_{mag}\right)$$

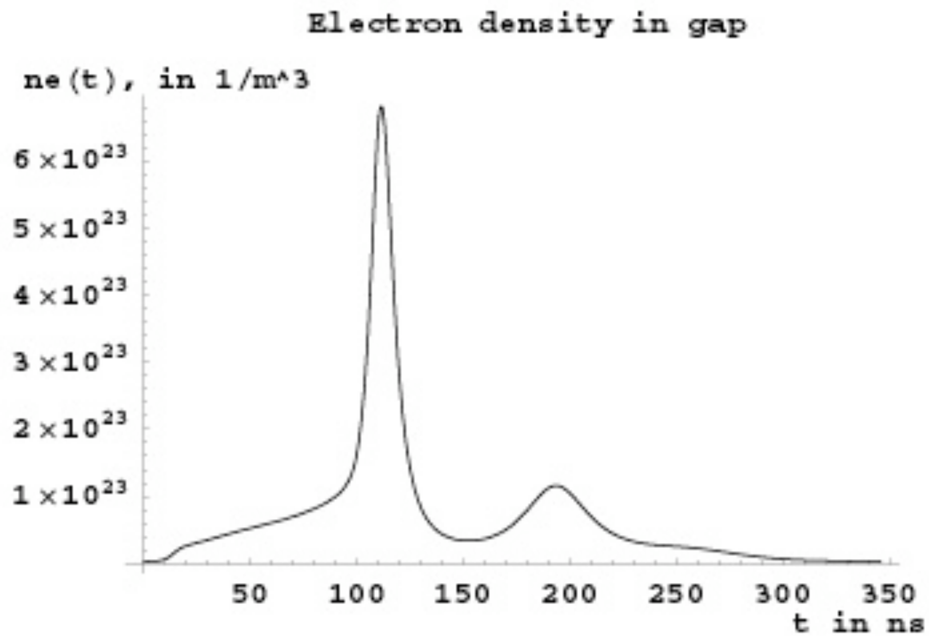


Equation for shock front radius r_s
(equilibrium of thermal and impact pressures):

$$v_s=\dot{r}_s=-\sqrt{\frac{k(ZT_e+T_i)}{M_{atom}}\frac{(a^2-{r_p}^2)}{({r_p}^2-{r_s}^2)}}$$

Pinch Radii and Electron density





Velocities of order ~20000 m/sec

Electron density changes very fast

Zero Dimensional Dynamic Pinch Model

Energy equations for electron Temperature:

$$N\frac{d}{dt}\left[\frac{3}{2}kZT_e + E_{ion}(Z)\right] = R\cdot I(t)^2 - p_e dV - Q_{ei} - \sum_i A_{ionstage}\cdot U_{rad,ionstage}(N,T_e,n_e)$$

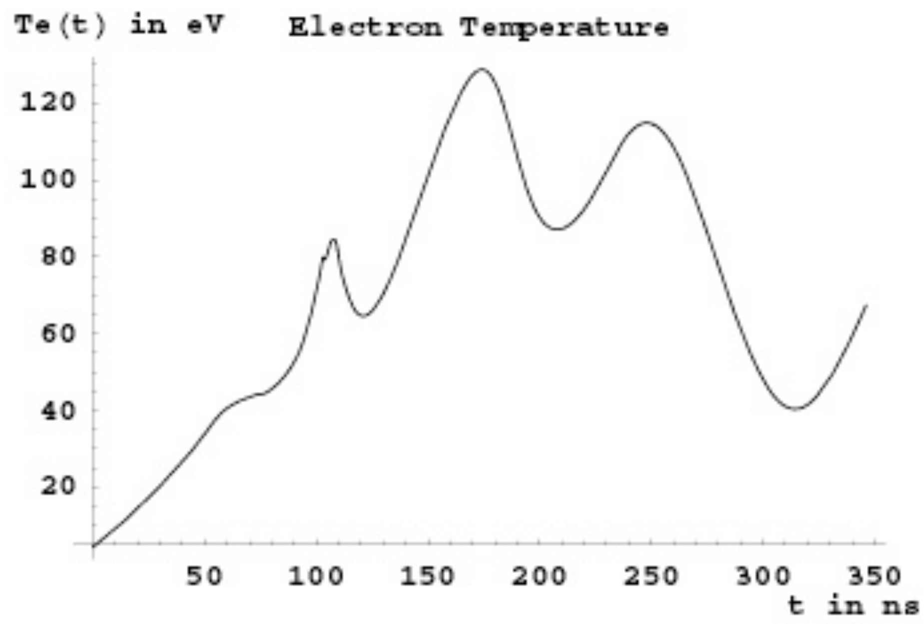
$U_{rad,ionstage}(N,T_e,n_e)$ **Radiation Power, tabulated from ADAS, based on CR population of excited states of each ionisation stage**

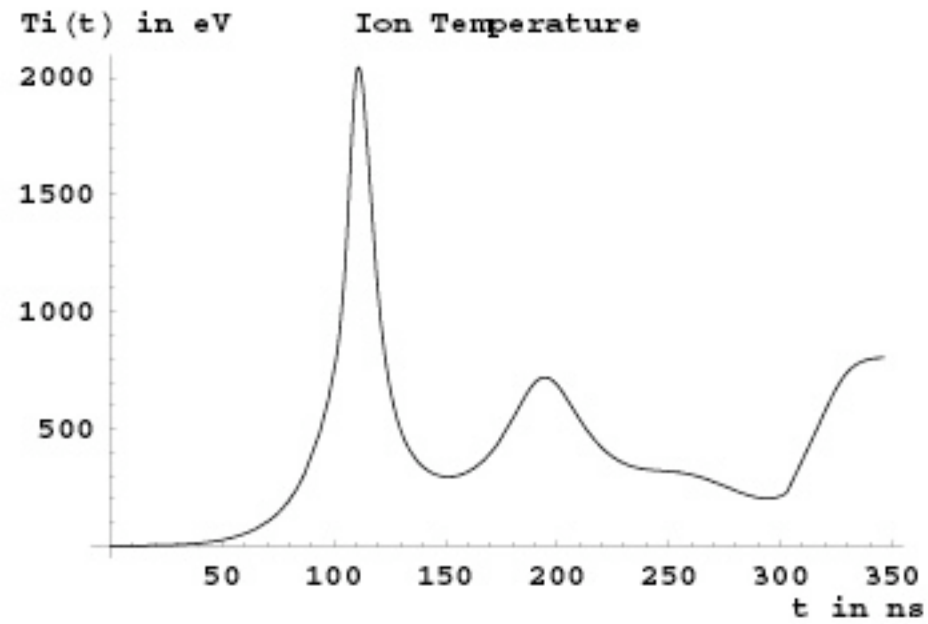
***R*: Spitzer Resistivity;** ***Q_{ei}*: Energy exchange electrons-ions**

Energy equations for ion Temperature:

$$N\frac{d}{dt}\left[\frac{3}{2}kT_i\right] = -NM_{atom}\frac{r_s v_s}{a^2}v_p{}^2 - p_i dV + Q_{ei}$$

Temperatures of Electrons/Ions





Electrons mostly heated ohmically, loose energy via ionisation, radiation

Ions heated by magnetic compression/shock heating, mostly hotter than electrons energy transferred to electrons at high densities

Zero Dimensional Dynamic Pinch Model

Ionisation dynamics to compute abundancies $A_{ionstage}$ of all ion stages:

$$\frac{dA_{ionstage}}{dt} = n_e \cdot \begin{pmatrix} A_{ionstage-1} \cdot IR_{ionstage-1}(T_e) - A_{ionstage} \cdot IR_{ionstage}(T_e) \\ + A_{ionstage+1} \cdot RR_{ionstage+1}(T_e) - A_{ionstage} \cdot RR_{ionstage}(T_e) \end{pmatrix}$$

$IR_{ionstage}, RR_{ionstage}$:

Ionisation and Recombination rates of each ionisation stage, including dielectronic processes, tabulated from ADAS

Axial Particle Losses: $$\frac{dN}{dt} = -2N \frac{v_{th,i}(T_i)}{l}$$

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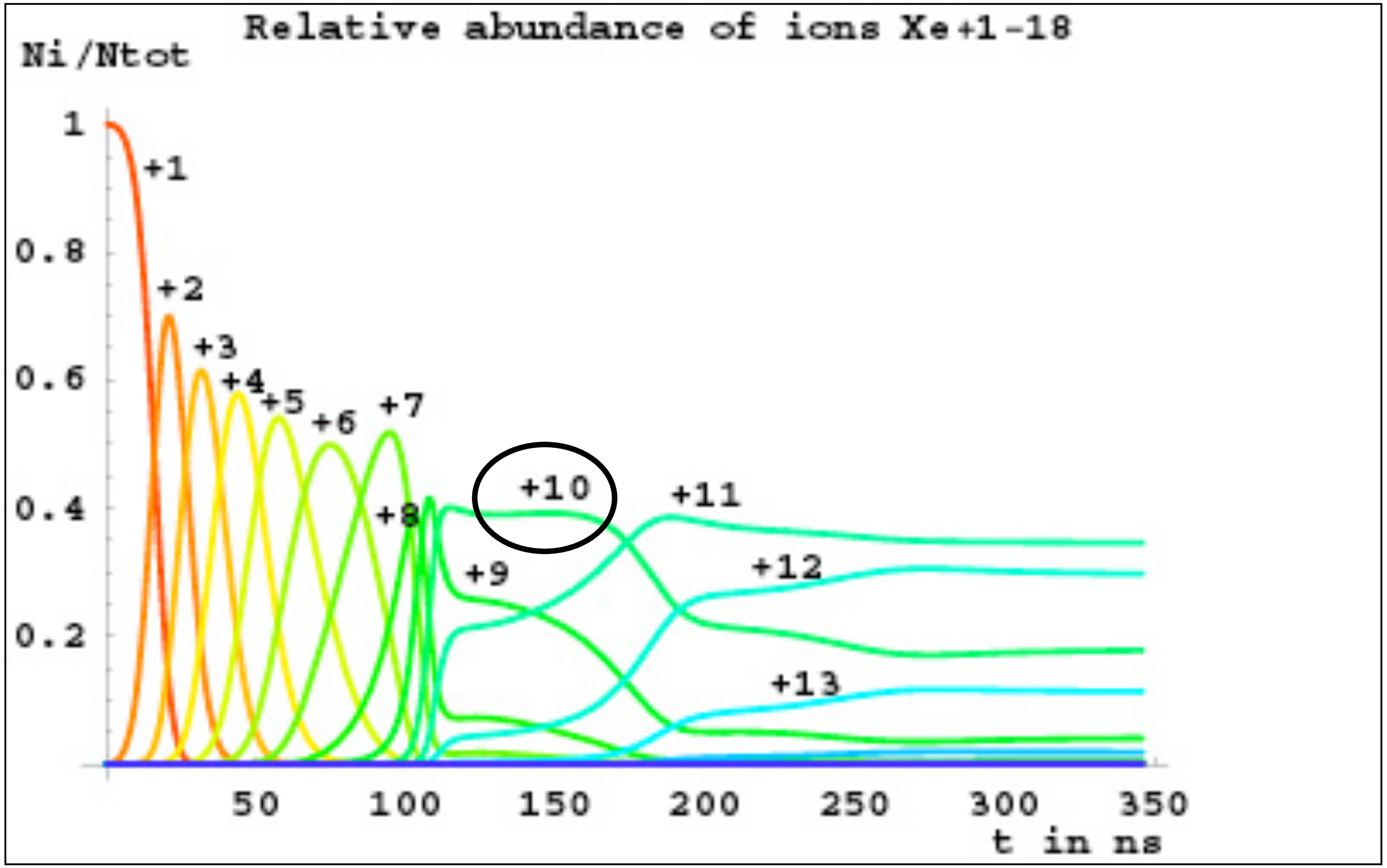
Ionisation dynamics



Ionisation/recombination must be treated dynamically
Abundancy of Xe^{+10} optimized, but < 40 %

Bypass caused by Photoionisation of outer gas

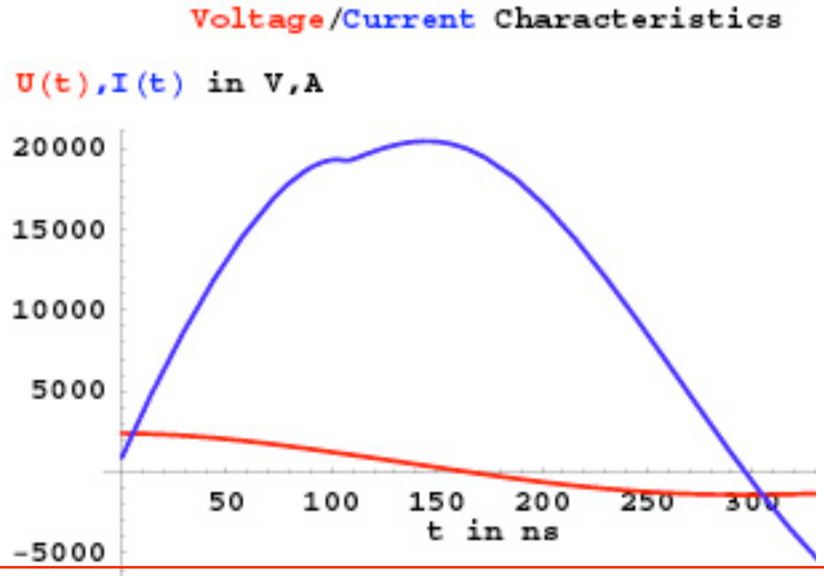
Dynamic ionisation of outer gas

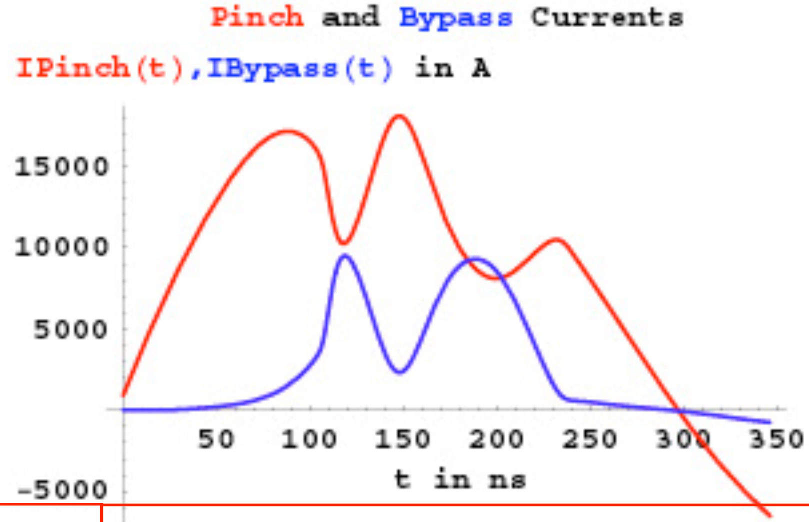
$$\frac{dZ_{out}}{dt} = \sigma_{PhotoIonisation} \cdot PhotonFlux \cdot \theta\left(h\nu - E_{ion}\left(Z_{out}\right)\right)$$

Bypass Resistance:
electrode fall + collisionless, quasineutral plasma

$$R_{Bypass} \cdot I_{Bypass} = V_{Bypass} = V_{Fall,By} + \frac{m_e}{2e}\left(\frac{j_{Bypass}}{e \cdot Z_{out} \cdot n_0}\right)^2$$

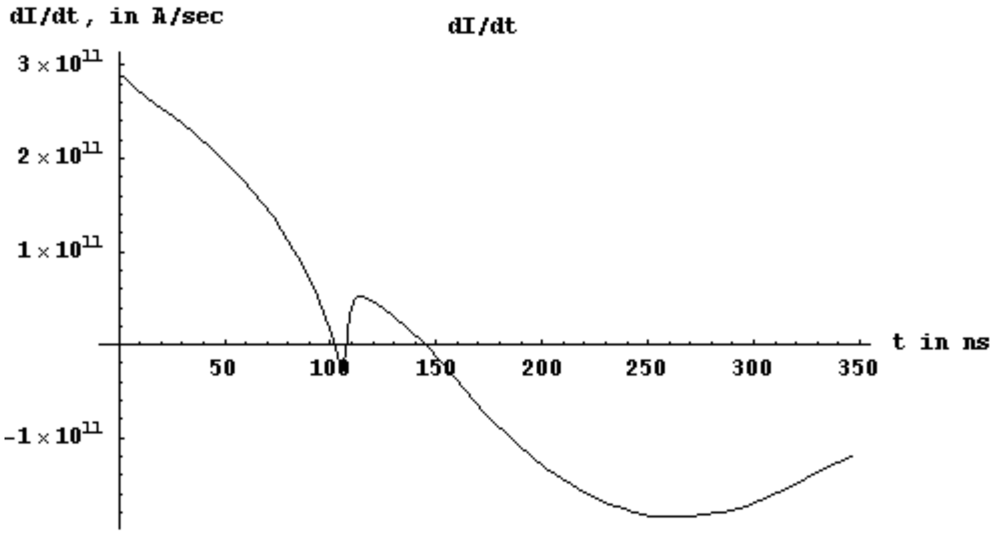
Current/Voltage Characteristics

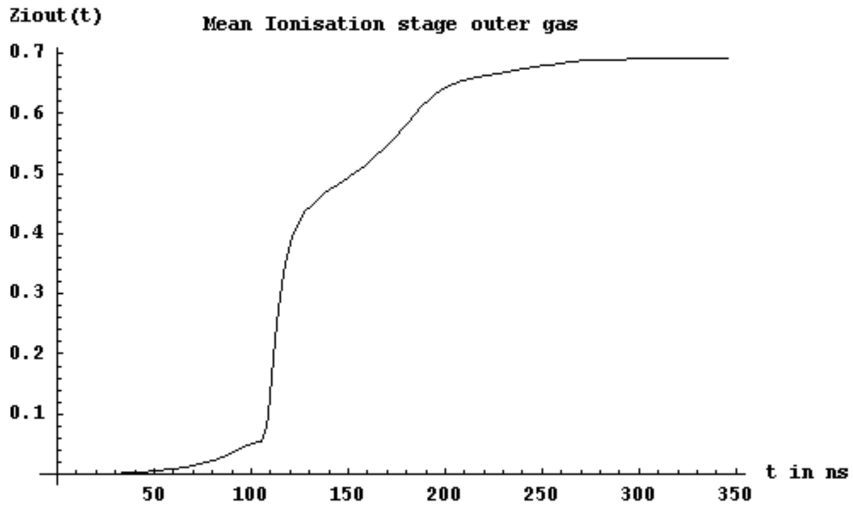




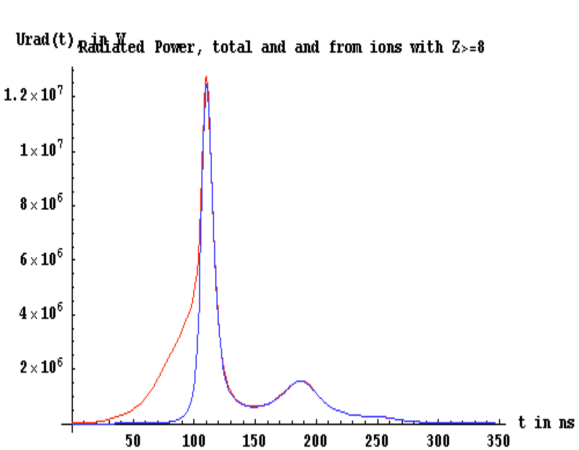
Important comparison with measurements, agreement requires bypass currents

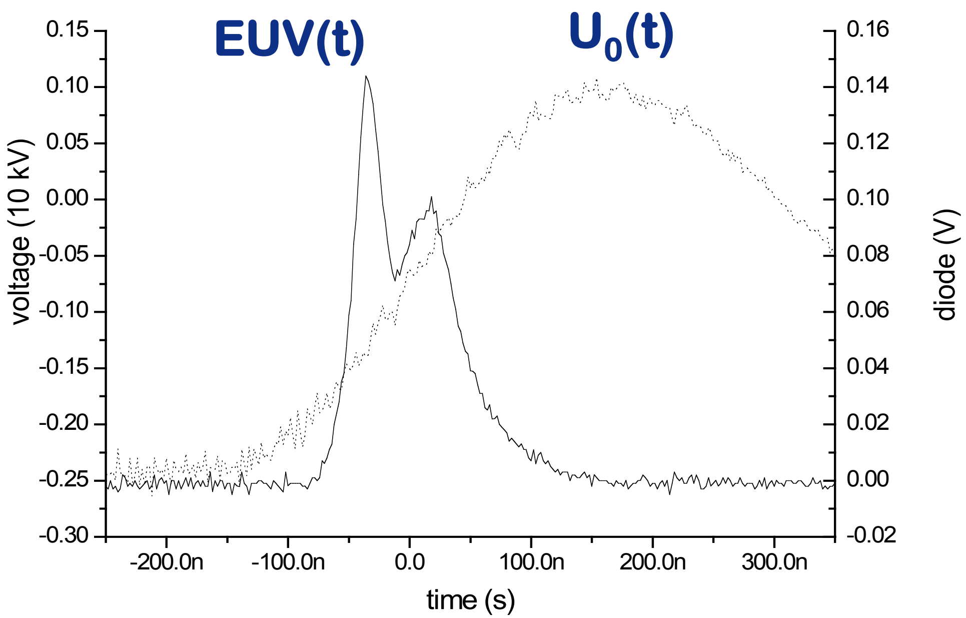
Photoionisation of outer gas opens Bypass channel

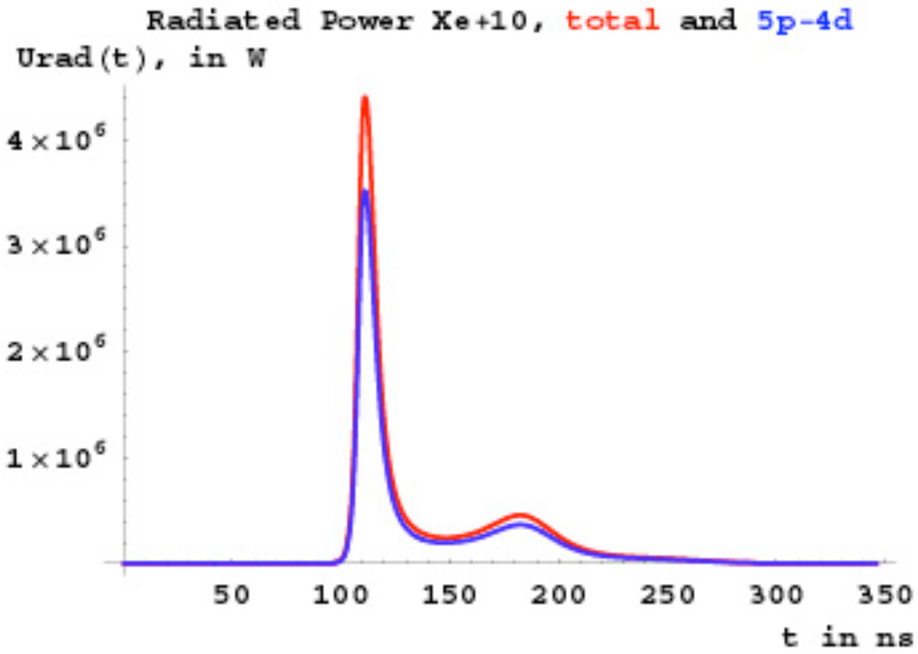




Radiation







Good agreement of transient radiation with experiments,
⇒ Optimization of CE

Disadvantages of Xenon-discharges:

- Xenon is "bad" radiator, too much out of band radiation, CE only ~ 0.5 %
  - Would require not tolerable input powers for production tool
- Bypass currents outside pinch-discharge difficult to suppress
- Cathode erosion ⇒
  - Change of pinch-shape ⇒ impact on etendue
  - Limited in power

Cathode hole erosion

A good EUV radiator must have many lines in inband regi

- half filled outer shells with high angular momentum
- Li^{2+} has only one (thick) line 2p-1s line at 13.5 nm
- 4f energy levels scale with nuclear charge,
  little dependence on Ionization stage **(O'Sullivan) :**

Xe ⇒ Sn

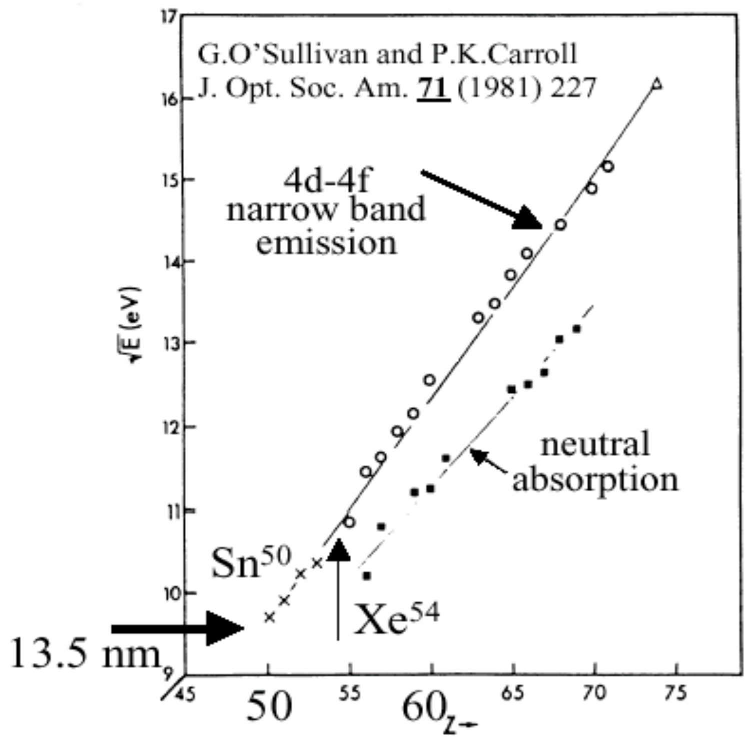
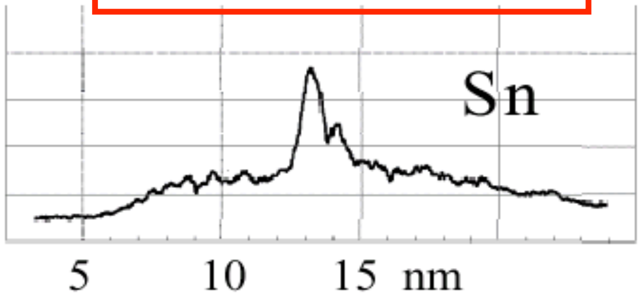


Fig. 5. Dependence of 4d–4f transition energies on atomic number Z. Open circles, this paper (Table 1); crosses, data from plasmas of tin through iodine; open triangles, assigned to tungsten in Tokomak plasma[9]; filled squares, absorption of neutral vapors.[10]

wavelength of 4d-4f
narrow band emission

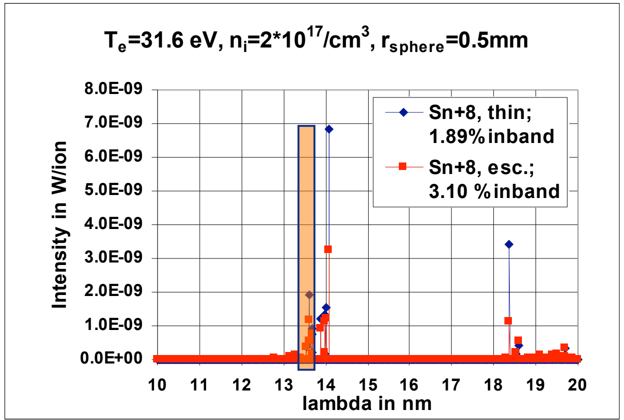
= determined by
atomic number

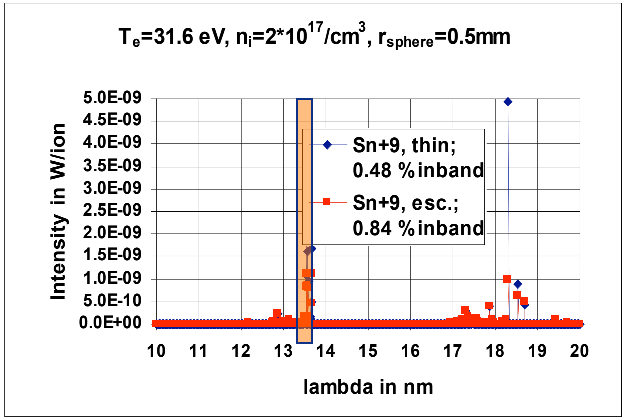
for 13 nm
Z=50 is the best
efficiency larger than
10% could be expected

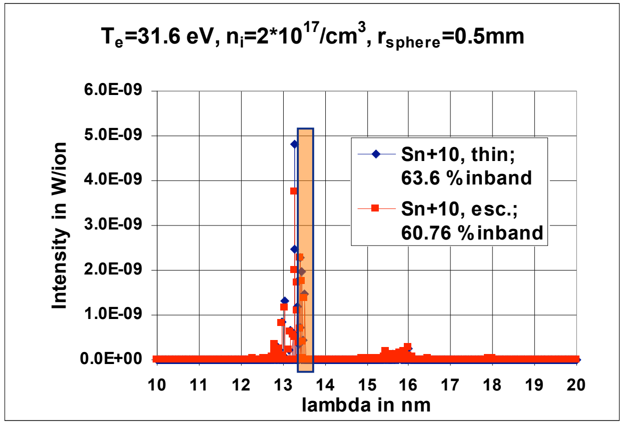


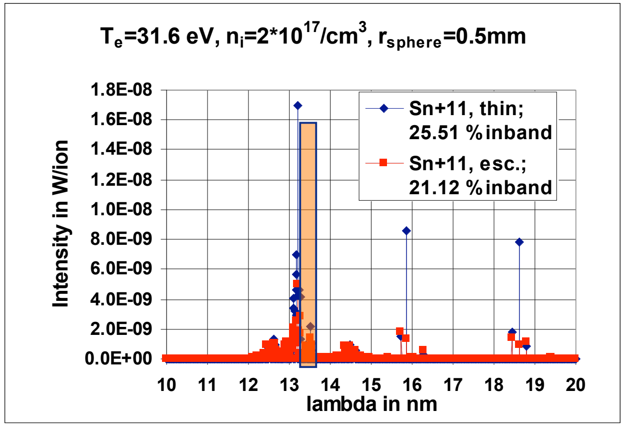
Tomie et.al. (Univ.Tokyo / Nikon),
Sematech EUV Source Workshop 2000

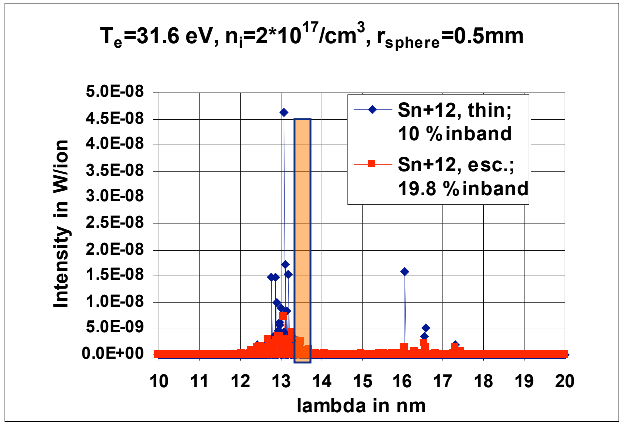
ADAS-Spectra of Tin ions Sn^{+8} - Sn^{+13}

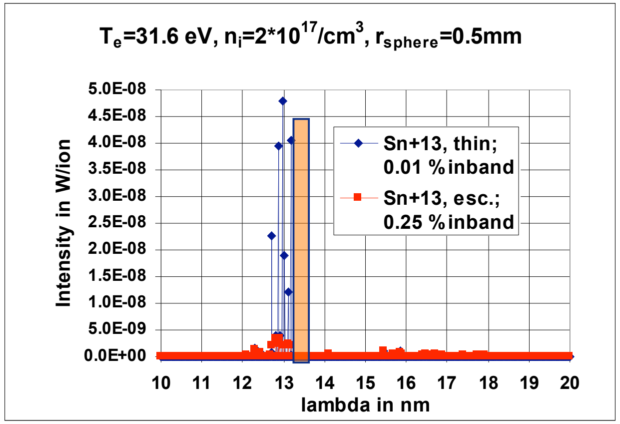






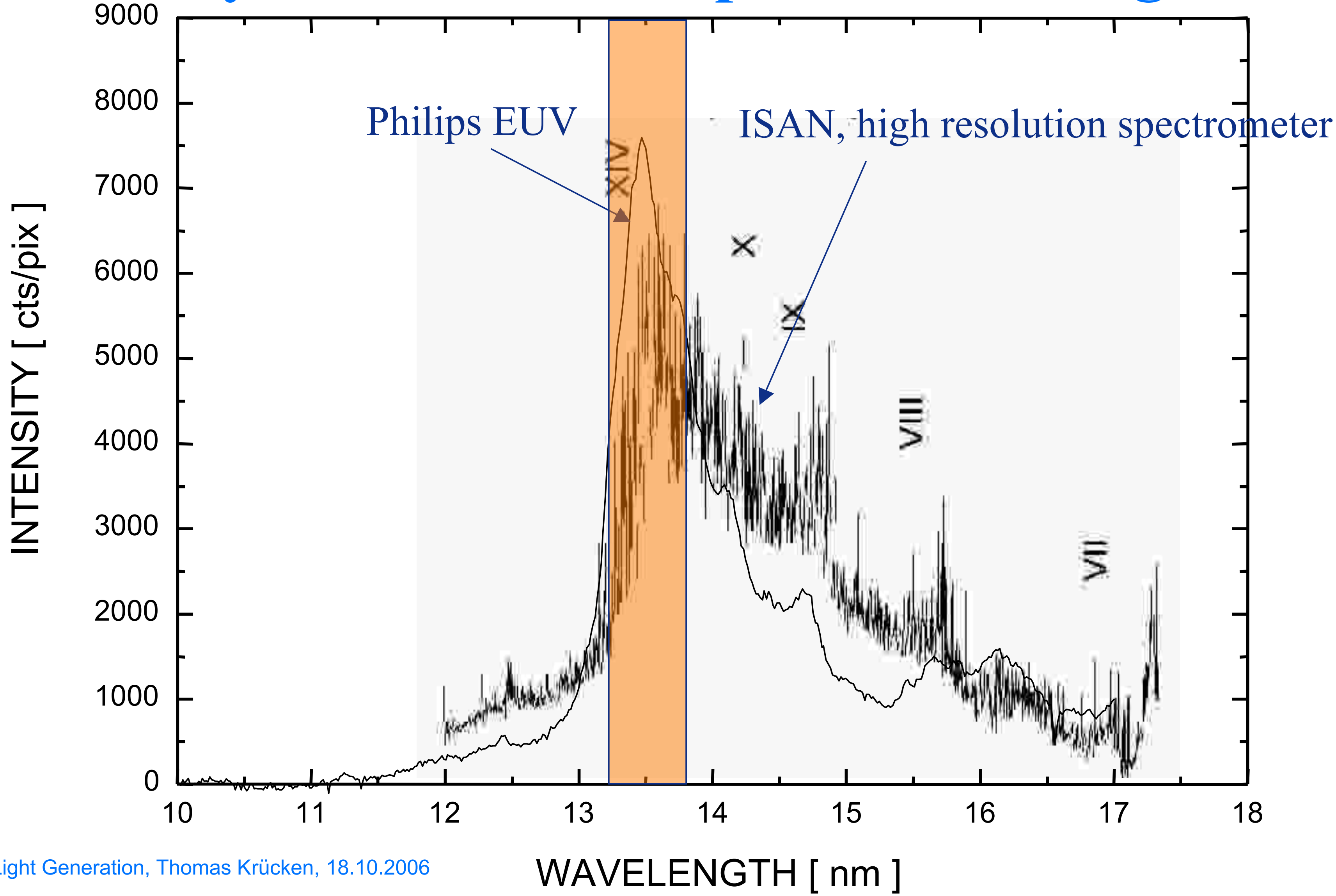




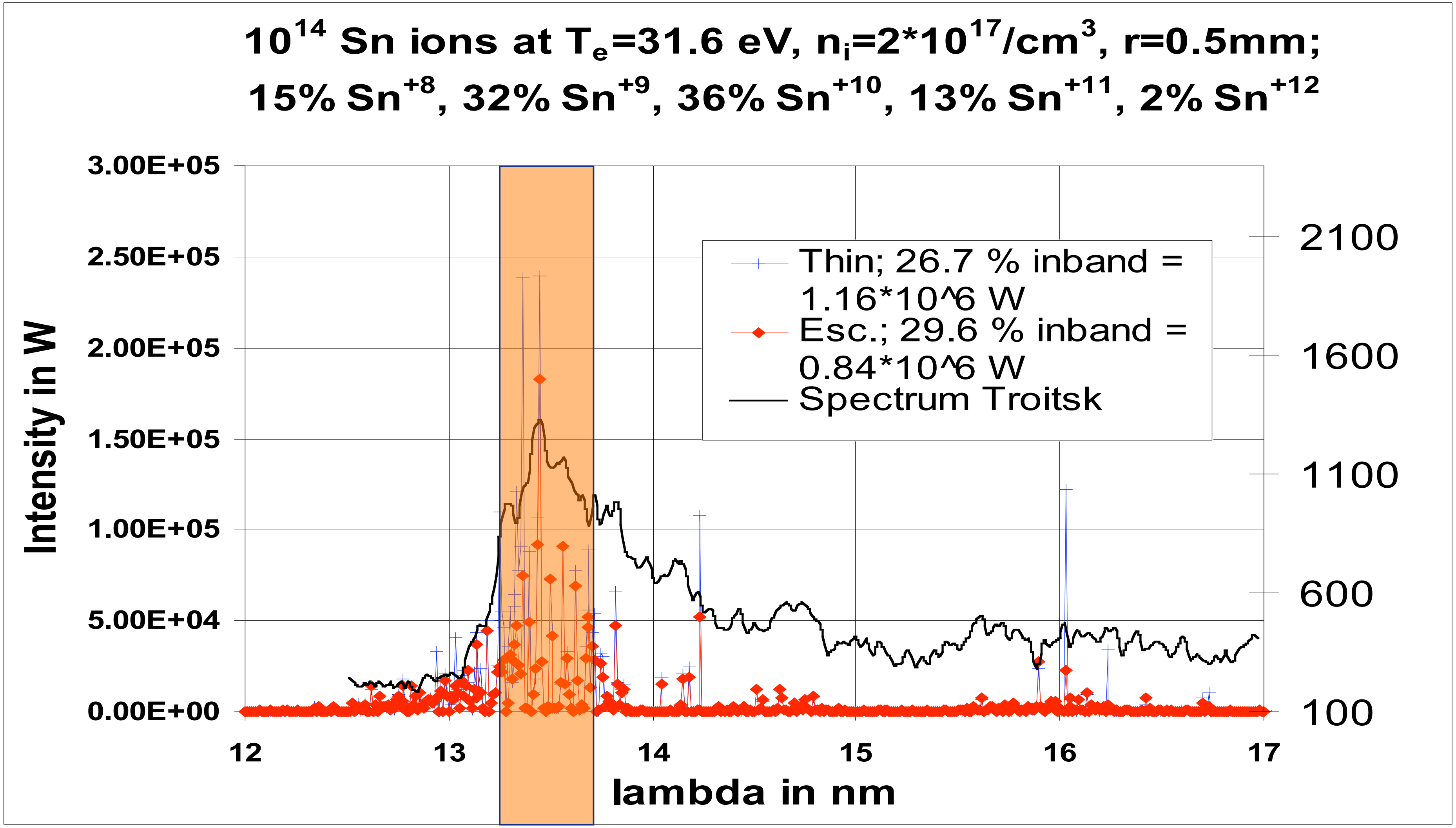


Many different ions have many energy levels and strong 4d-4f transitions near 91 eV, also 5p-4d lines from some ions

Measured Tin EUV spectra
Many lines, almost impossible to assign



Spectrum of Tin ion mix



Inband spectral efficacy near 13.5 nm ~ 5 times better than Xe !!!

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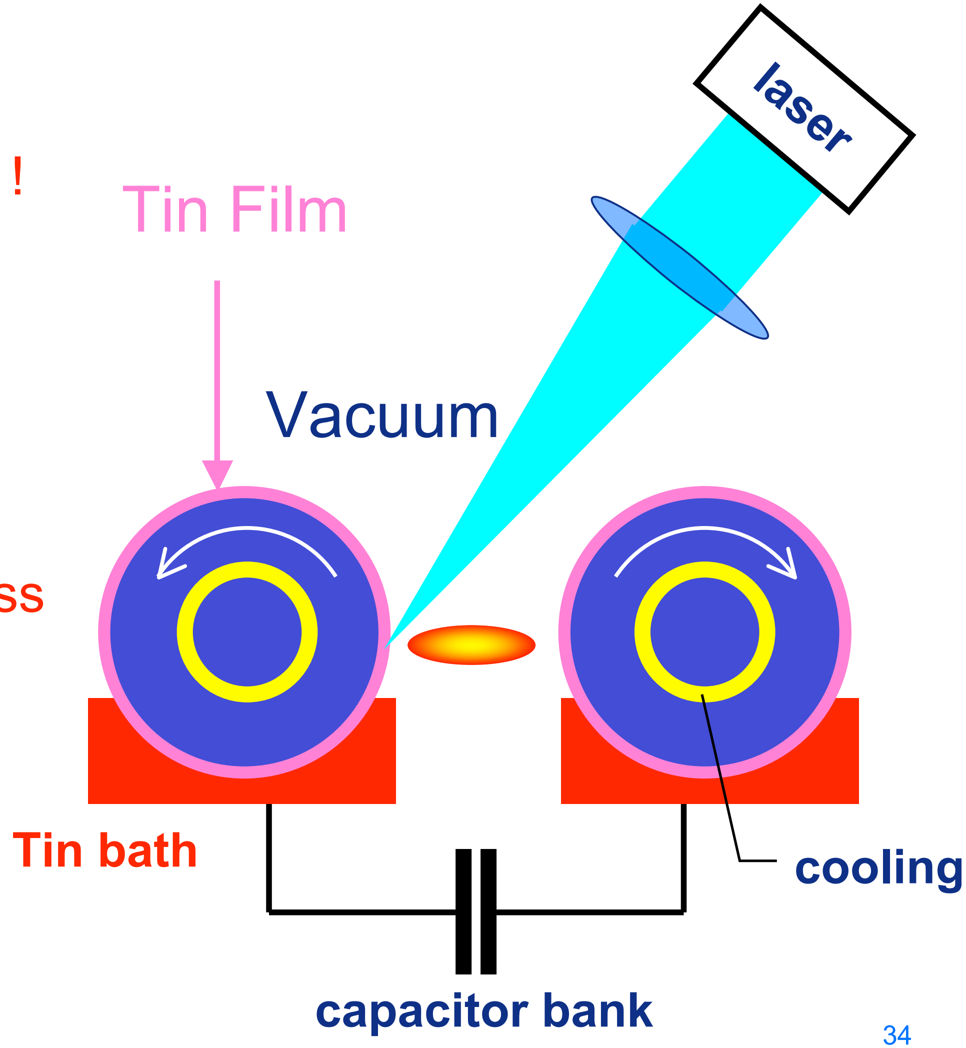
New High Power Source Concept

- Laser Triggered Vacuum Spark
- Rotating electrodes
  - ⇒ Scalability to very high power !
- Regenerating liquid tin surface
  - ⇒ Electrode erosion problem fundamentally solved !
- Liquid metal cooling
  - ⇒ Very efficient to remove excess heat !

- CE ~ 2% achieved



Very difficult to model plasma

- Laser ablation + Vapor expansion into vacuum
  - highly inhomogeneous density profile in space and time
  - Self absorption of Laser light ⇒
    - Plasma heating/ionization
    - Reduced ablation
- Ignition when first ablated material reaches other electrode
- High current phase:
  - Further evaporation of Tin from electrodes
  - Thermal expansion and magnetic compression
  - Electrical current profiles/Skin effect …
  - Strong inhomogenities in space (also axial) and time of
    - Density
    - Temperatures
    - Ionization stage
  - Strong self absorption of emitted (inband!) radiation
  - Instabilities

Problems of Tin-discharge

- Debris, Tin will condensate everywhere !
- Tin must be kept away from first optical elements (collector), only ~15 cm away from discharge
  - – Tin layers on collector < 1 nm !!!
  - – Debris Mitigation required
    - Discharge operates in vacuum
    - EUV transparency requires also vacuum
  - – Cleaning of optical elements
- Many engineering aspects

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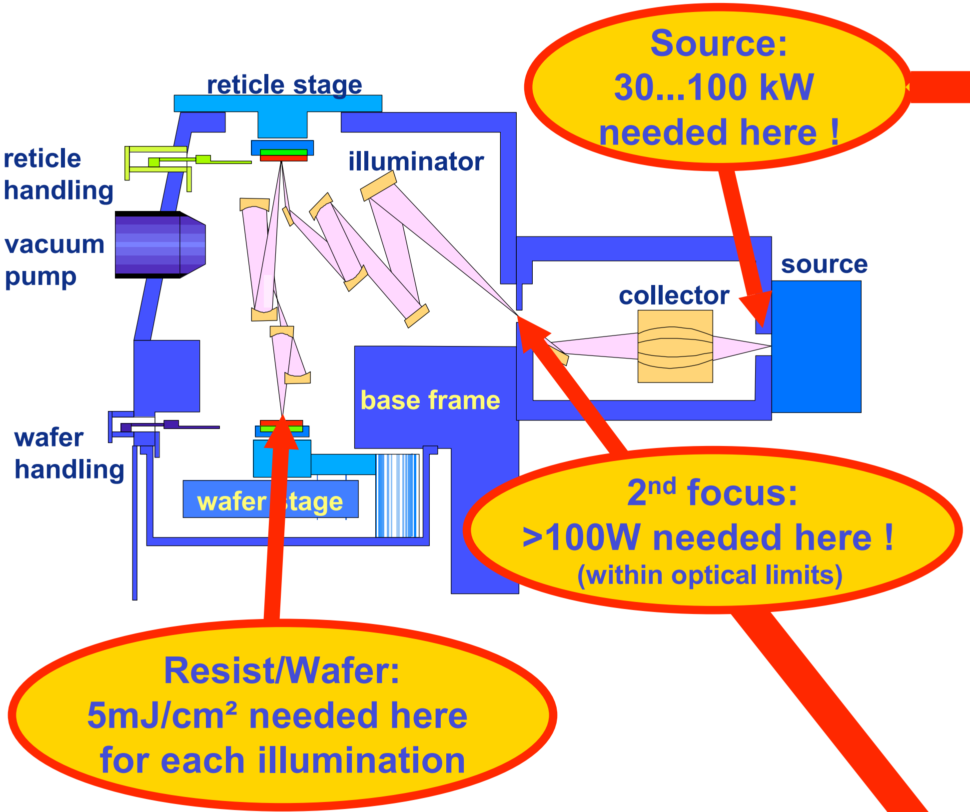
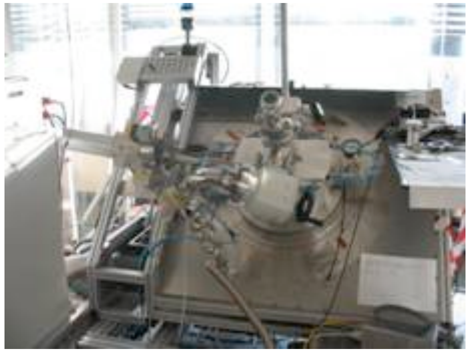
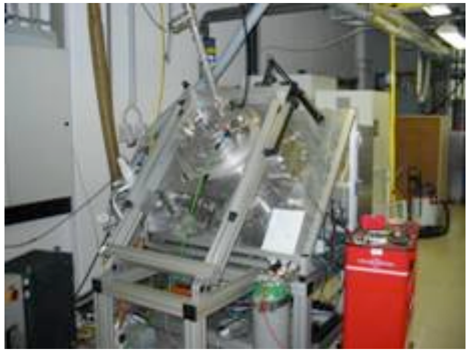
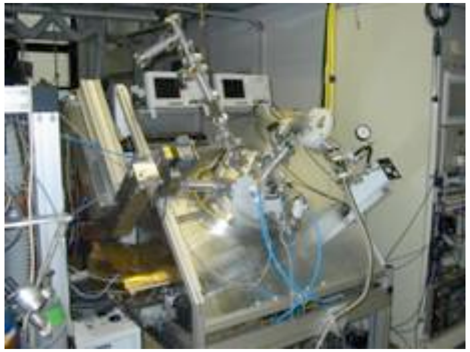
Throughput model for a commercial tool, 80 wafers/hour

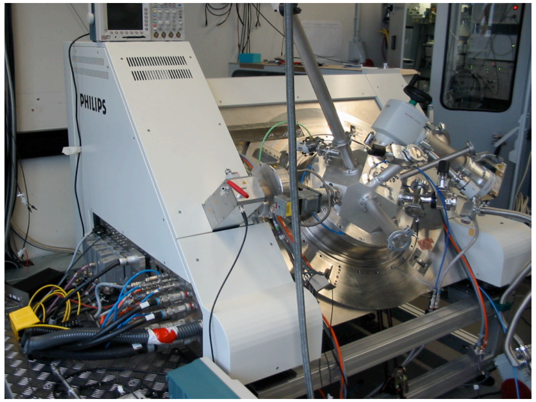
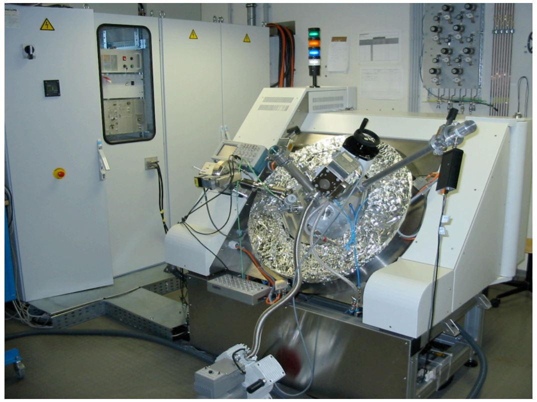


	Xenon	Tin
electrical input	30.000 W	30.000 W
conversion efficiency CE	0.5 %	2 %
Inband EUV in 2π	150 W	600 W
collection efficiency ColE	30 %	35 %
collectable EUV	45 W	210 W
system transmission	50 %	50 %
collectable EUV in 2nd focus	22.5 W	105 W

Experimental and Demo sources

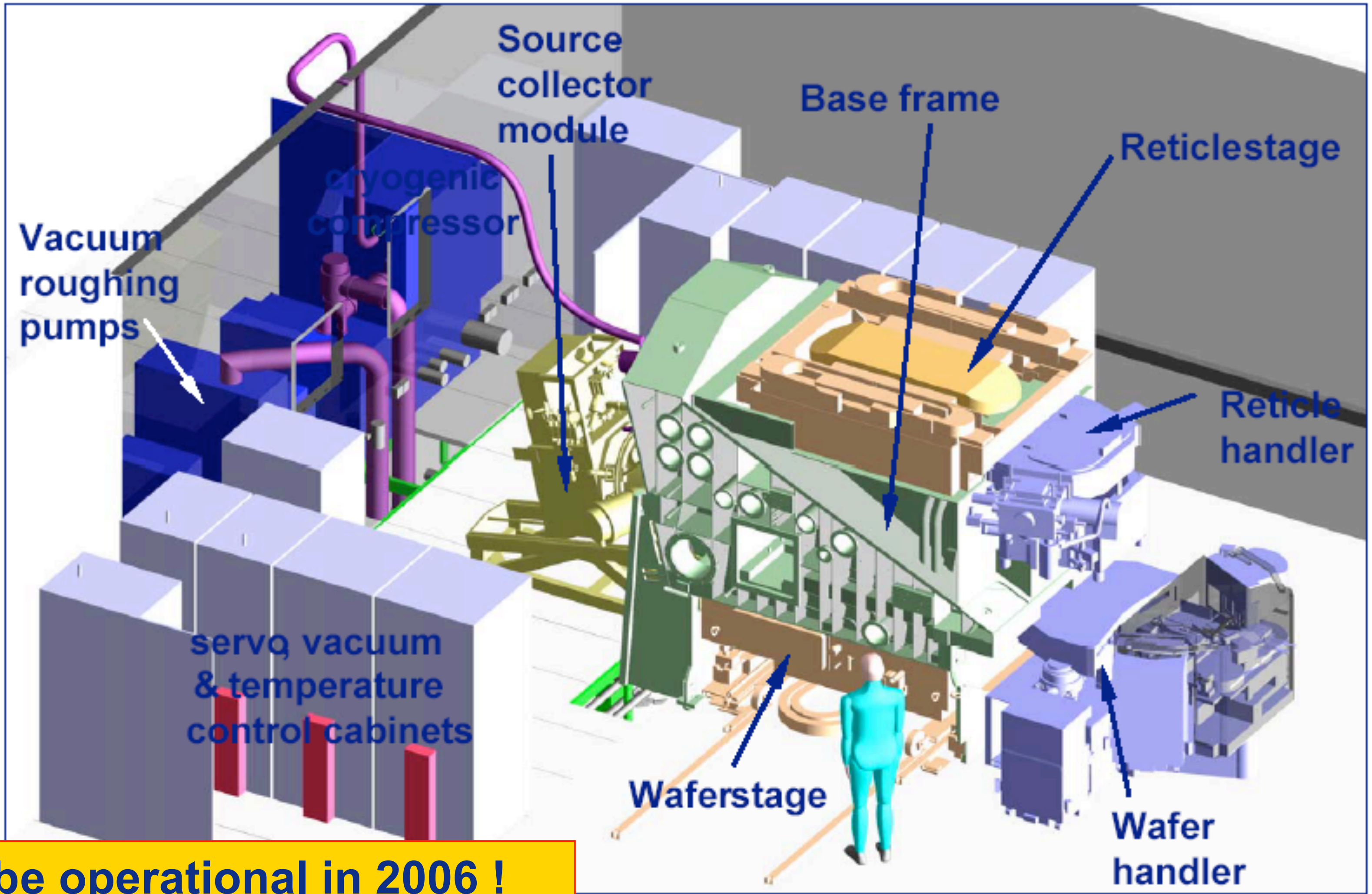




Source research and development


Commercial grade source

Alpha Demo Tool in Building 9



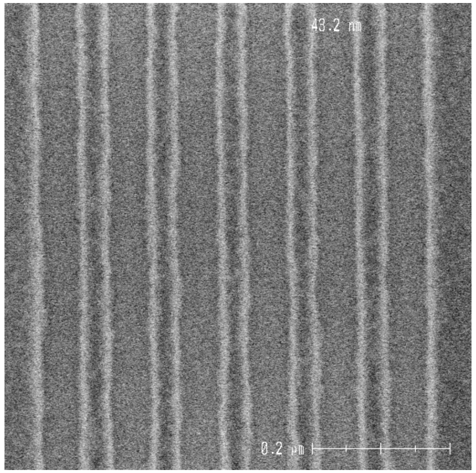
To be operational in 2006 !

Key value drivers for light source:

- Power → tool throughput
- Lifetime → tool uptime

Excellent Resolution and Line Edge Roughness

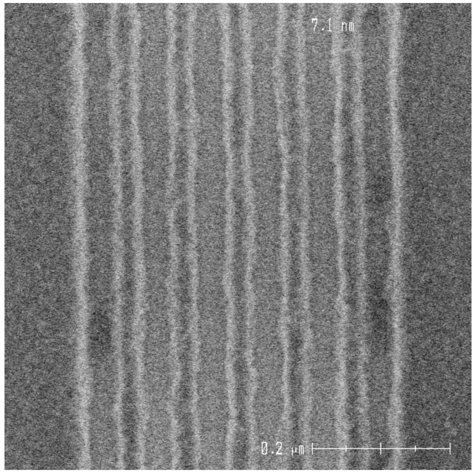
50 nm L/S



LER = 2.7 nm

ave TF LER = 4.0 nm

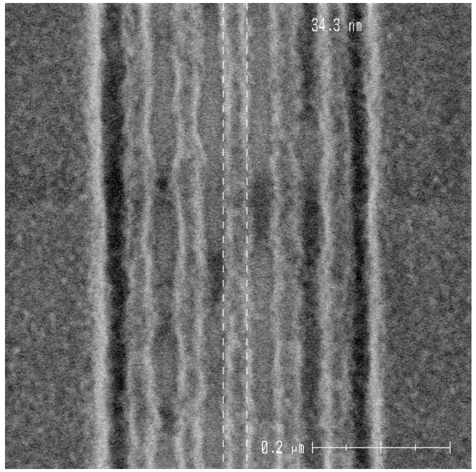
40 nm L/S



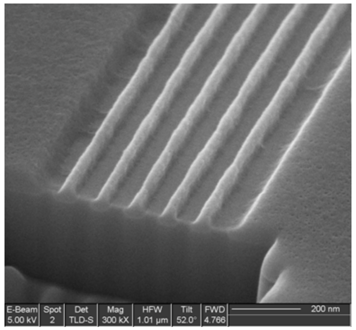
LER = 5.1 nm

ave TF LER = 6.1 nm

35 nm L/S



FIB Cross section: 50 nm L/S resist profile



Resist: MET-2D, ~18 mJ/cm^2
NA=0.25
σ= 0.5 (conventional illumination)
no process development yet

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