

Injection dependence of spontaneous radiative recombination in c-Si: experiment, theoretical analysis, and simulation

Pietro P. Altermatt

Frank Geelhaar

Thorsten Trupke, Ximing Dai, Axel Neisser*

Ernst Daub

University Hannover

ETH Zurich (now: AMD Sunnyvale)

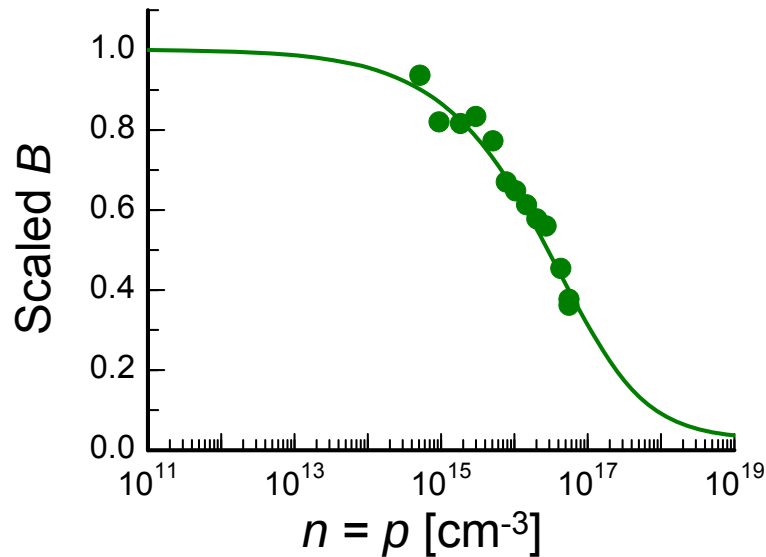
University of NSW, Sydney (*now: HMI Berlin)

Siltronic AG, Burghausen

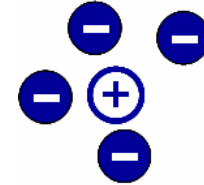
Basic mechanism

$$R_{rad} = B(np - n_{i,eff}^2)$$

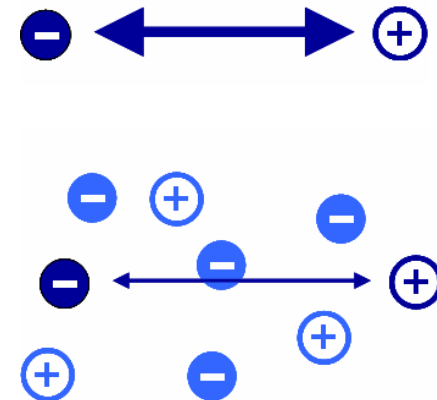
$\uparrow$
 $B_0 g_{eh}$



Injection-dependent g_{eh}



Coulomb-enhancement



Screening
of Coulomb forces

Outline

- Measurement of B :
 - symmetrical plasma ($n=p$), method I
 - asymmetrical plasma ($n>p$, $n<p$), method II+III
- Calculation and parameterisation
- Simulation of a classic experiment
- Outlook

Outline

- Measurement of B :
 - symmetrical plasma ($n=p$), method I
 - asymmetrical plasma ($n>p$, $n<p$), method II+III
- Calculation and parameterisation
- Simulation of a classic experiment
- Outlook

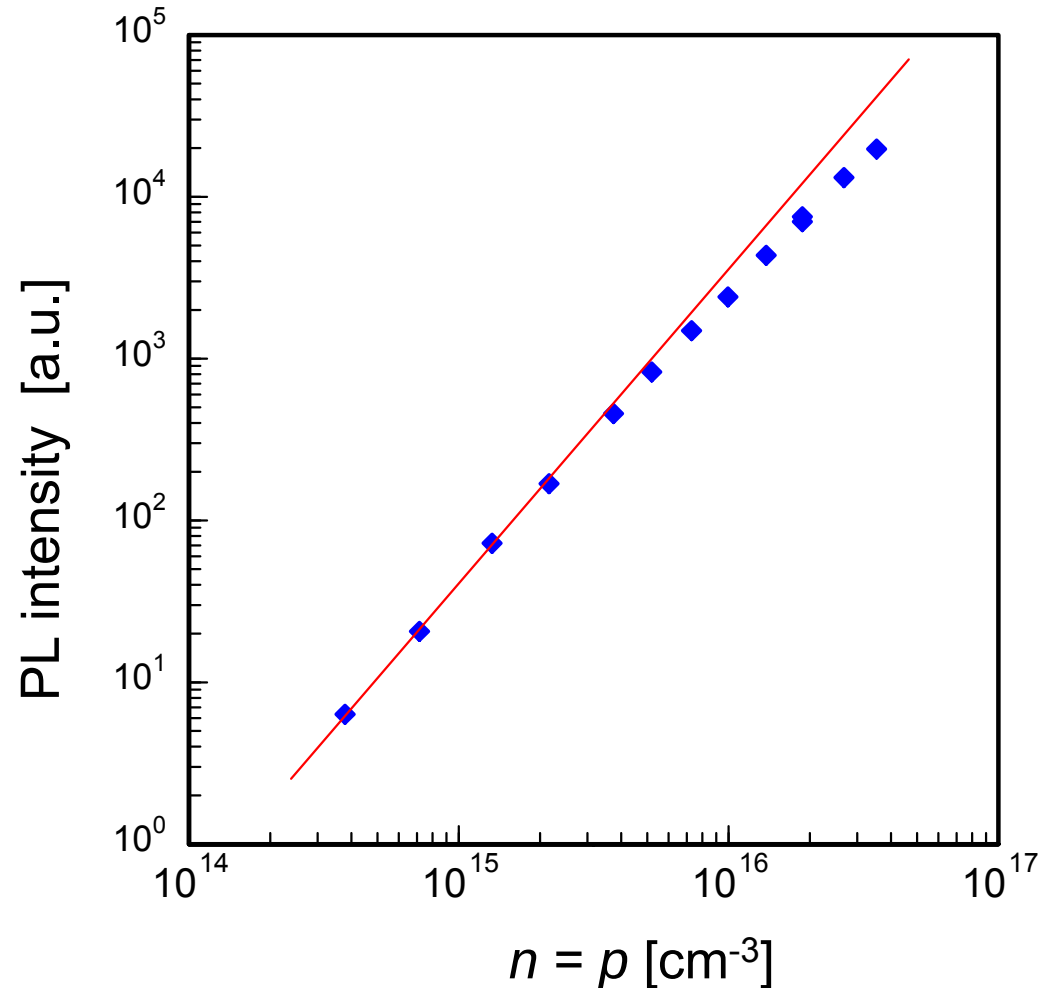
Measuring B : Method I

$$R_{rad} = B(np - n_{i,eff}^2)$$

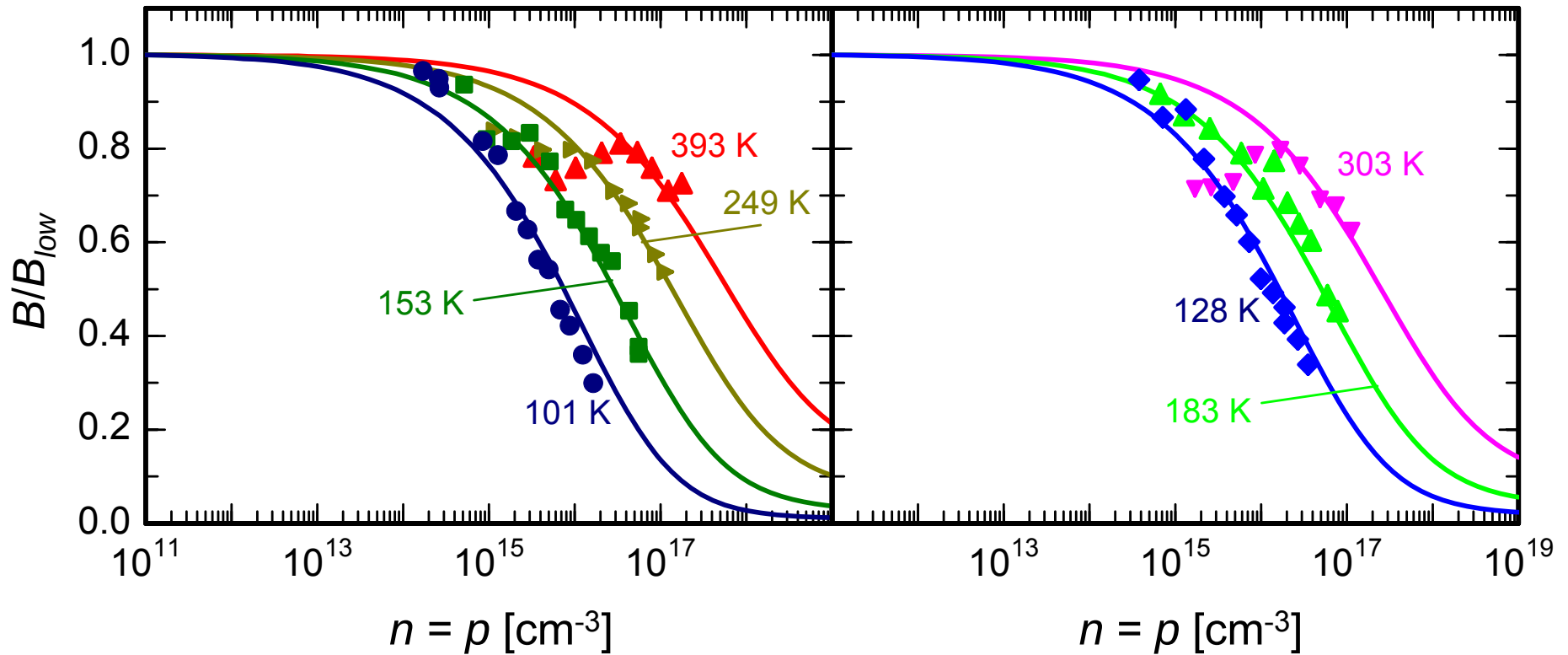
Measurement of
 R_{rad} , p and n

$\rightarrow B$

$$\frac{B}{B_{low}}$$



Measuring B : Method I



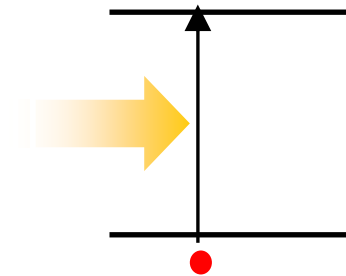
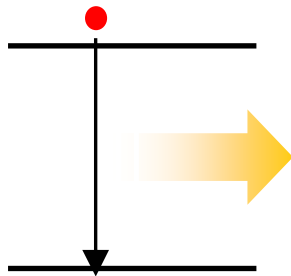
Symmetrical plasma

Outline

- Measurement of B
 - symmetrical plasma ($n=p$), method I
 - asymmetrical plasma ($n>p, n<p$), method II+III
- Calculation and parameterisation
- Simulation of a classic experiment
- Outlook

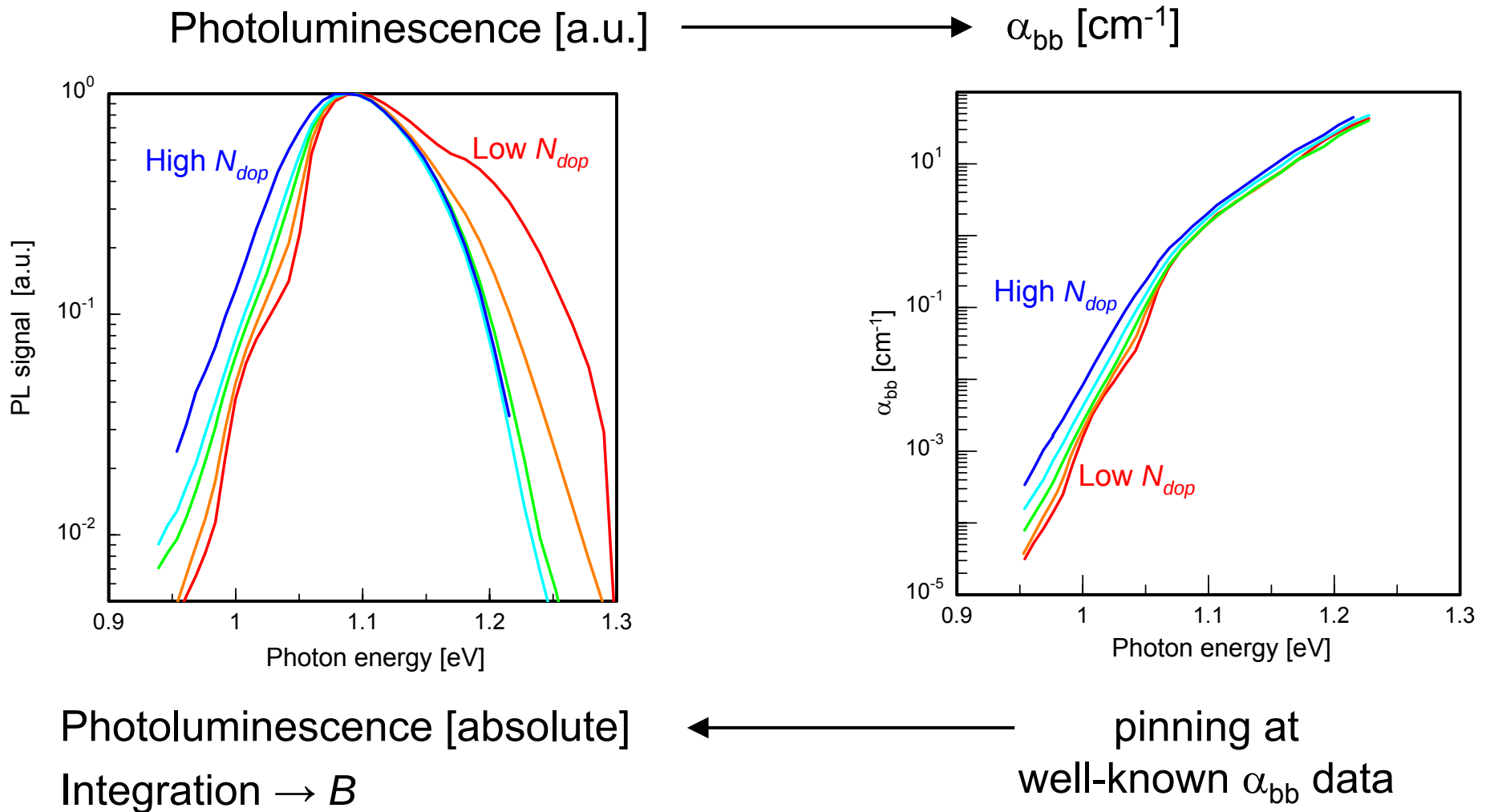
Measuring B : Method II

Measurement of α_{bb} and applying generalised Planck equation

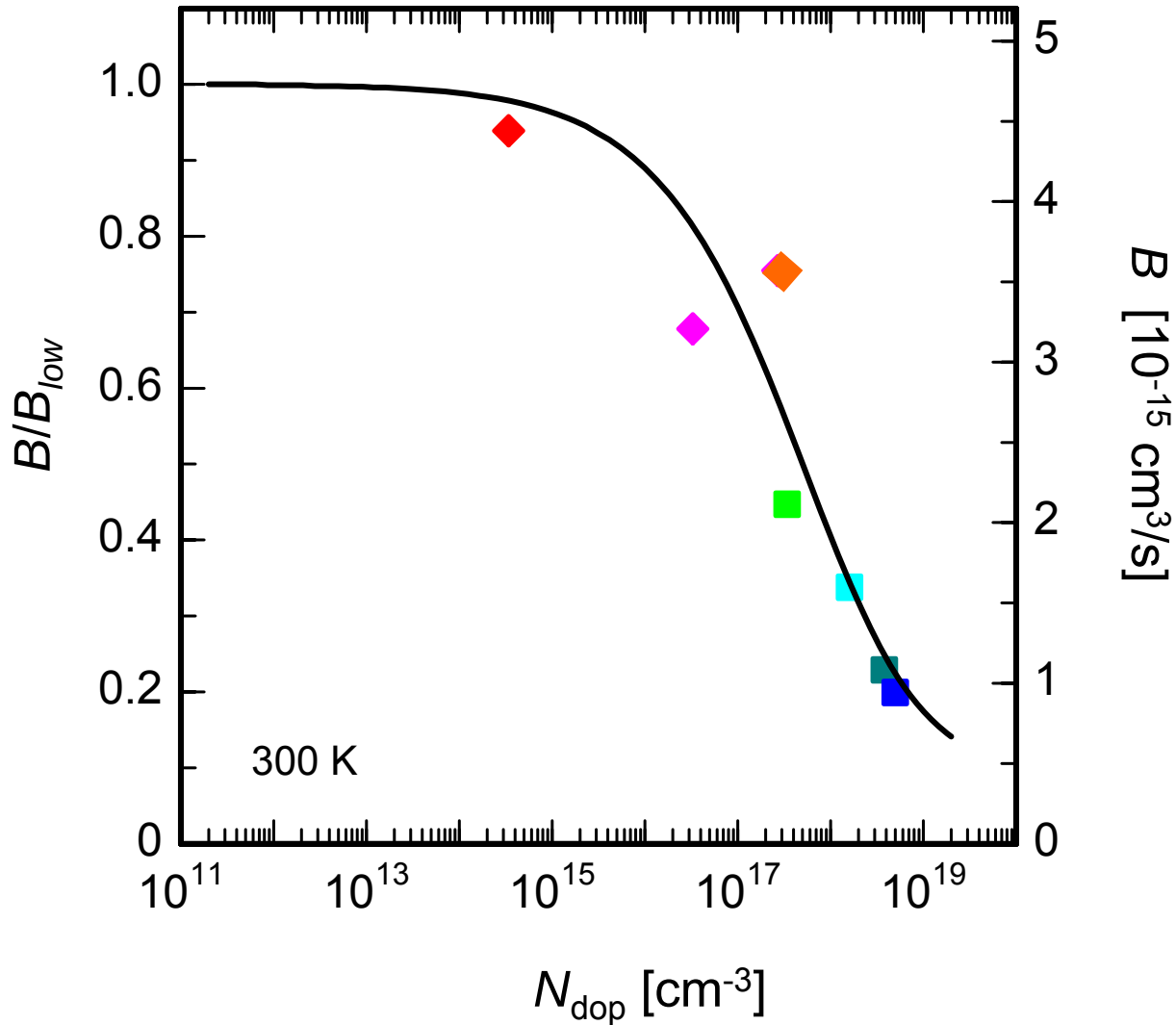


$$B = \frac{1}{n_{i,\text{eff}}^2 \pi^2 \hbar^3 c_0^2} \int_0^\infty N^2 E_{\text{ph}}^2 \alpha_{bb} e^{-E_{\text{ph}}/kT} dE_{\text{ph}}$$

Measuring B : Method II

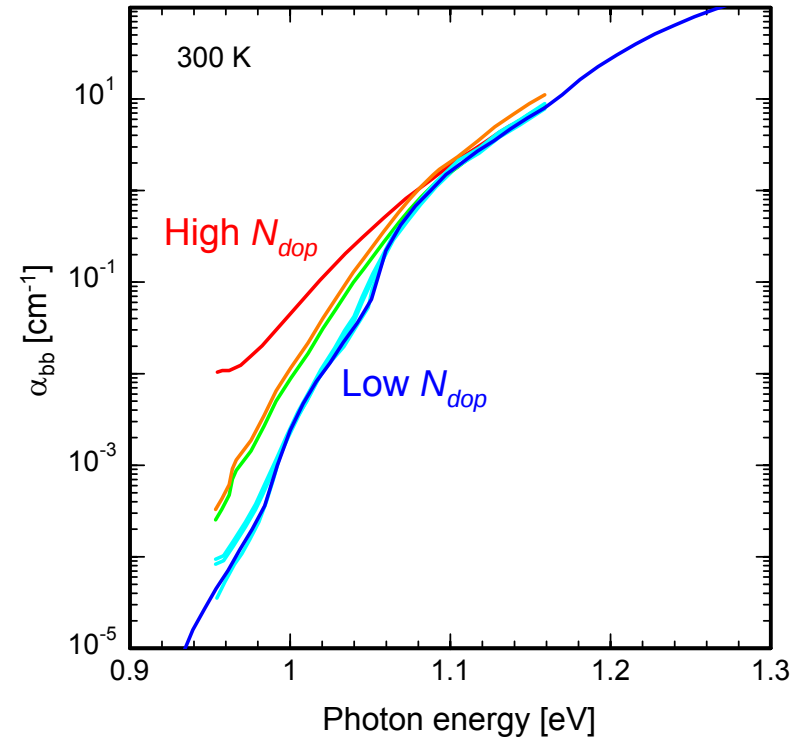
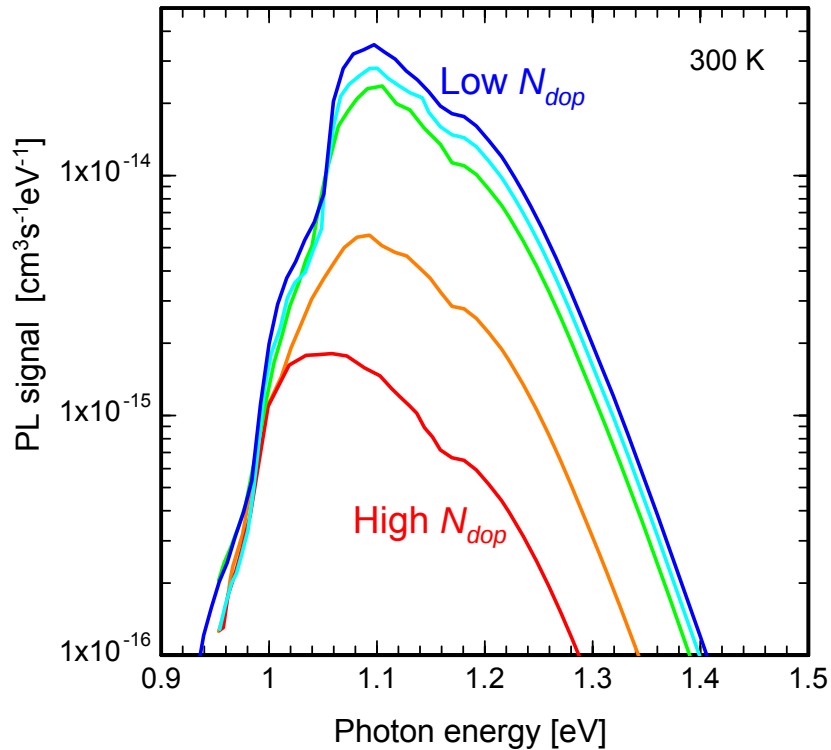


Measuring B : Method II



Measuring B : Method III

Photo-response

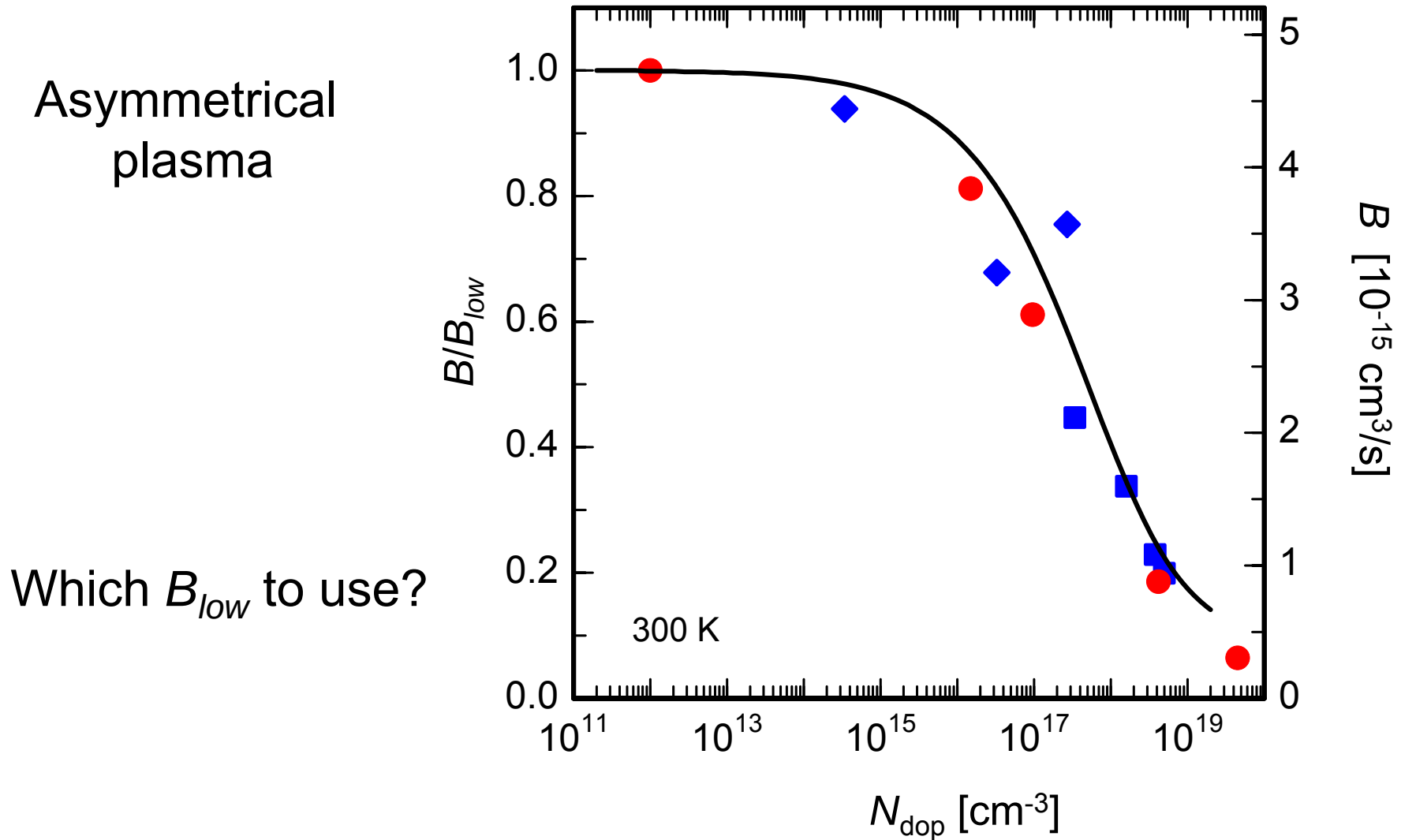


Photoluminescence [absolute]
Integration $\rightarrow B$

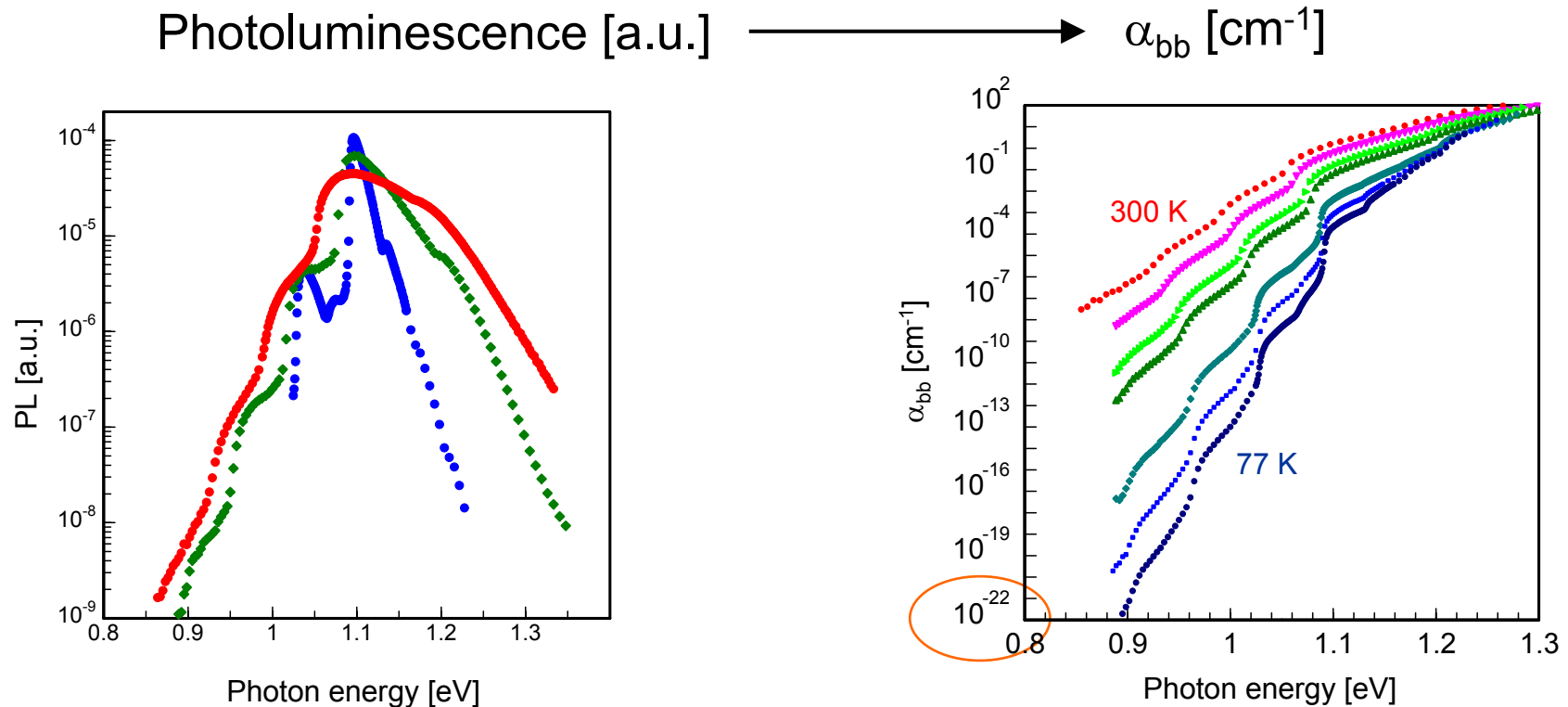
pinning at
well-known α_{bb} data



Measuring B : Method II+III



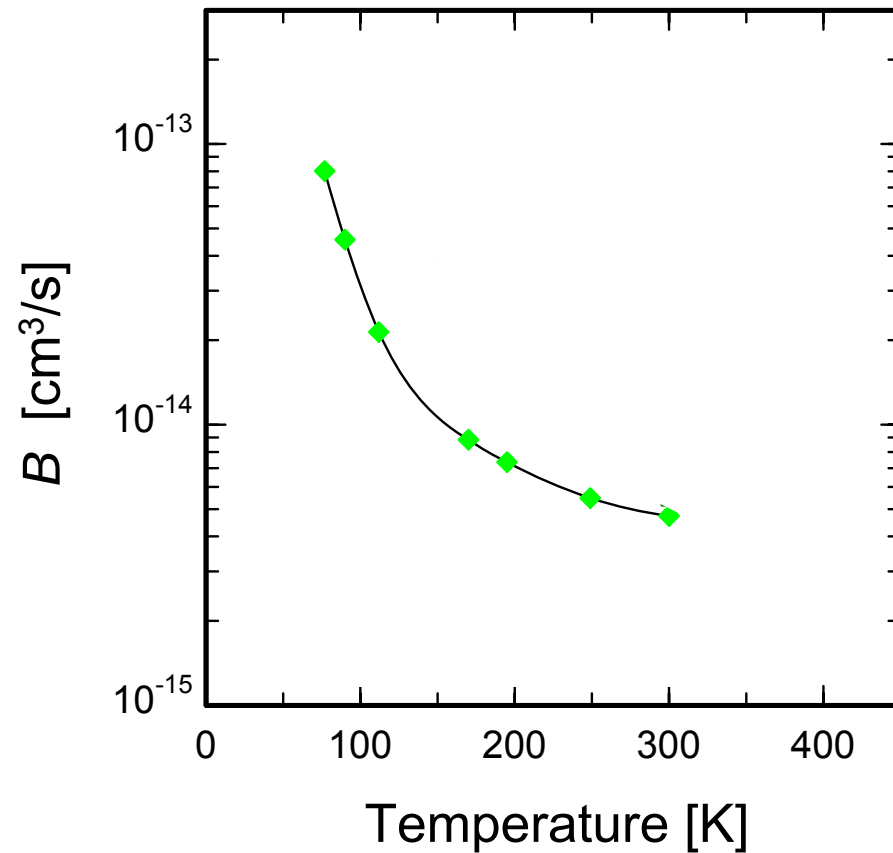
Measuring B_{low} : Method II



Photoluminescence [absolute]
Integration $\rightarrow B = 4.73 \times 10^{-15} \text{ cm}^3 \text{ s}^{-1}$

pinning at
well-known α_{bb} data

Measuring B_{low} : Method II



Outline

- Measurement of B
 - symmetrical plasma ($n=p$), method I
 - asymmetrical plasma ($n>p$, $n<p$), method II+III
- **Calculation and parameterisation**
- Simulation of a classic experiment
- Outlook

Calculations

Overlap of wavefunctions:

$$g_{eh} = \frac{\Lambda_{eh}^3}{4\pi} \sum_{\nu} |R_{\nu 0}(0)|^2 \exp(-E_{\nu 0} / kT)$$

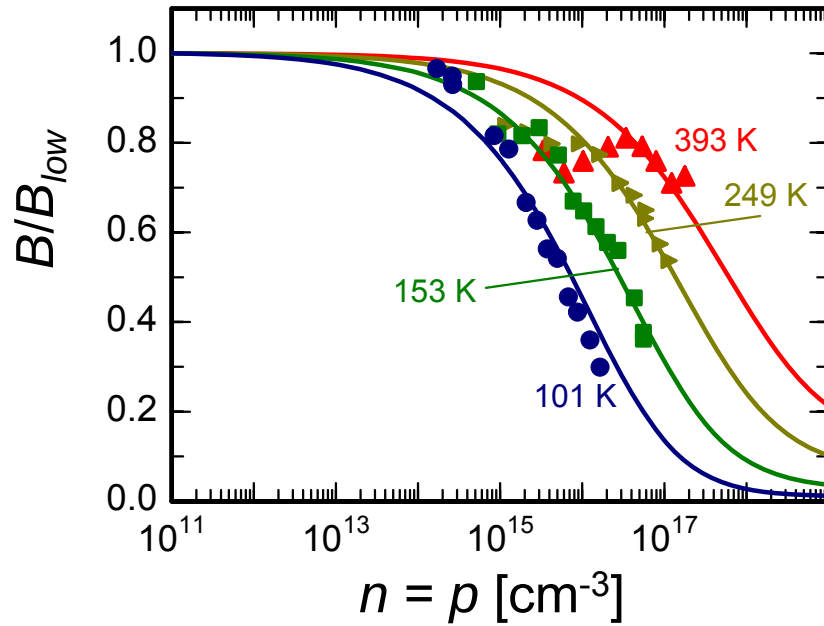
Debye potential (screening):

$$w_{eh}(r) = -e^2 / (4\pi\epsilon_r\epsilon_0) \exp(-\kappa r) / r$$

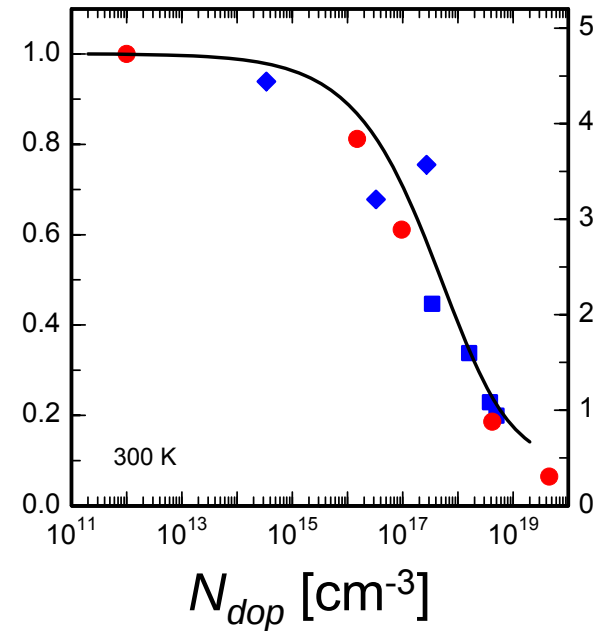
Boltzmann statistics:

$$\kappa^2 = (e^2 / kT\epsilon_r\epsilon_0)(n + p)$$

Calculations



Symmetrical plasma



Asymmetrical plasma

Parameterisation

$$\frac{B}{B_{\text{low}}} = b_{\text{min}} + \frac{b_{\text{max}} - b_{\text{min}}}{1 + \left(\frac{n+p}{b_1}\right)^{b_2} + \left(\frac{n+p}{b_3}\right)^{b_4}}$$

Parameterisation

Physical model interface (MPI) of Dessis

$$\frac{B}{B_{\text{low}}} = b_{\text{min}} + \frac{b_{\text{max}} - b_{\text{min}}}{1 + \left(\frac{n+p}{b_1}\right)^{b_2} + \left(\frac{n+p}{b_3}\right)^{b_4}}$$

$$= r_{\text{max}} + \frac{r_{\text{min}} - r_{\text{max}}}{1 + (T/r_1)^{r_2}}$$

$$= s_{\text{max}} + \frac{s_{\text{min}} - s_{\text{max}}}{1 + (T/s_1)^{s_2}}$$

$$= w_{\text{max}} + \frac{w_{\text{min}} - w_{\text{max}}}{1 + (T/w_1)^{w_2}}$$

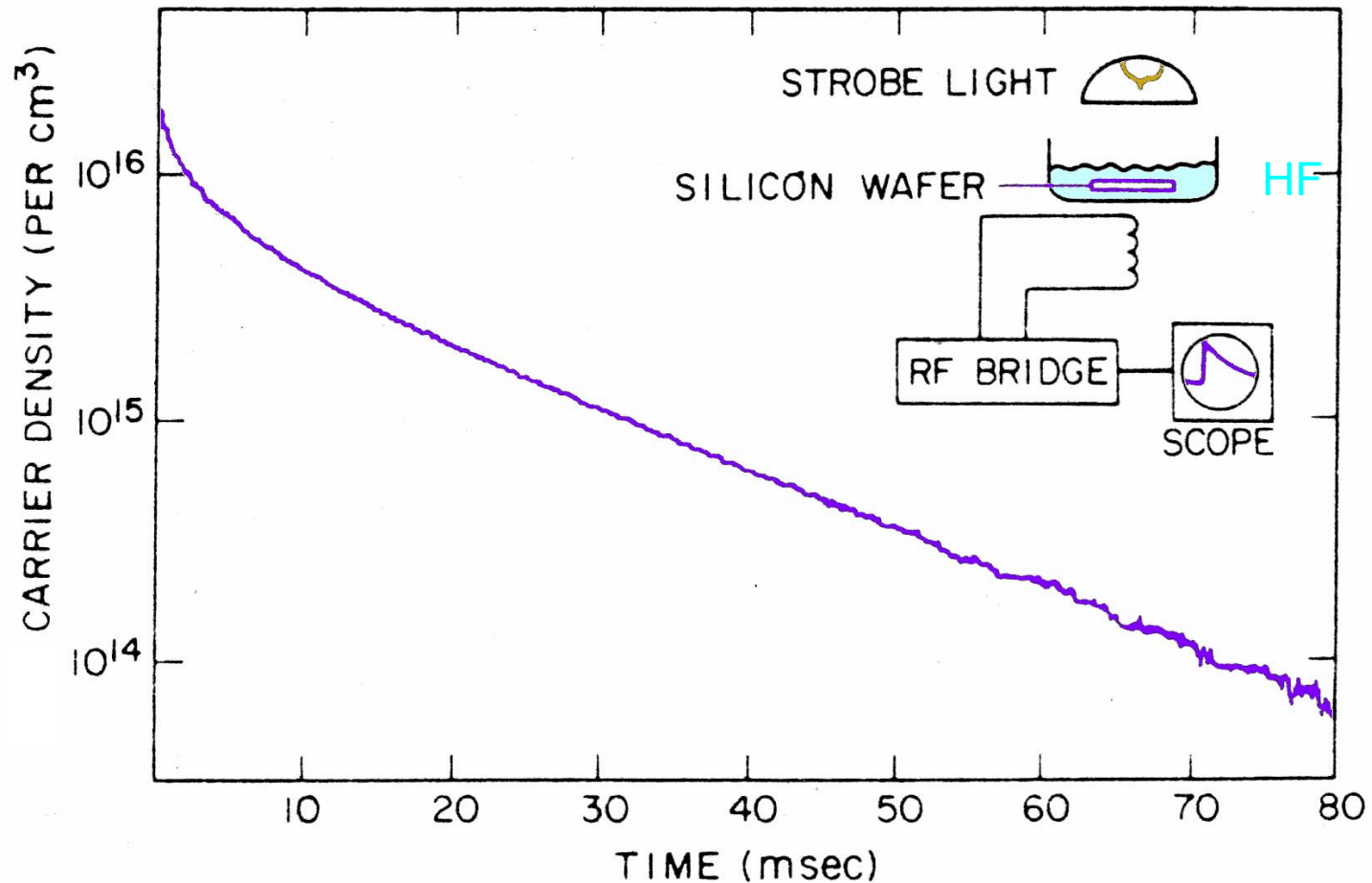
$b_{\text{max}} =$	1.00		$b_2 =$	0.54	$b_4 =$	1.25	
$r_{\text{max}} =$	0.20	$r_{\text{min}} =$	0.00	$r_1 =$	320	$r_2 =$	2.50
$s_{\text{max}} =$	1.5×10^{18}	$s_{\text{min}} =$	1×10^7	$s_1 =$	550	$s_2 =$	3.00
$w_{\text{max}} =$	4.0×10^{18}	$w_{\text{min}} =$	1×10^9	$w_1 =$	365	$w_2 =$	3.54

Outline

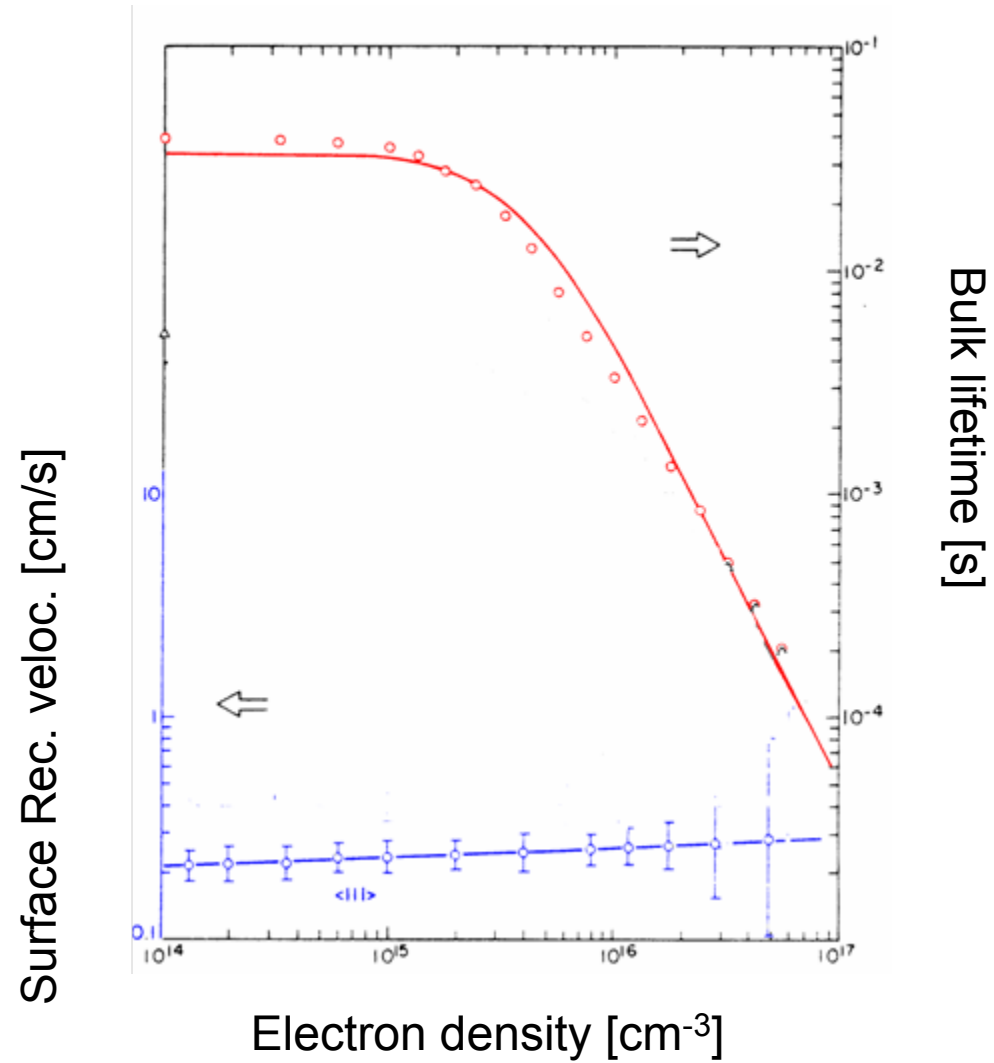
- Measurement of B
 - symmetrical plasma ($n=p$), method I
 - asymmetrical plasma ($n>p$, $n<p$), method II+III
- Calculation and parameterisation
- **Simulation of a classic experiment**
- Outlook

Simulations

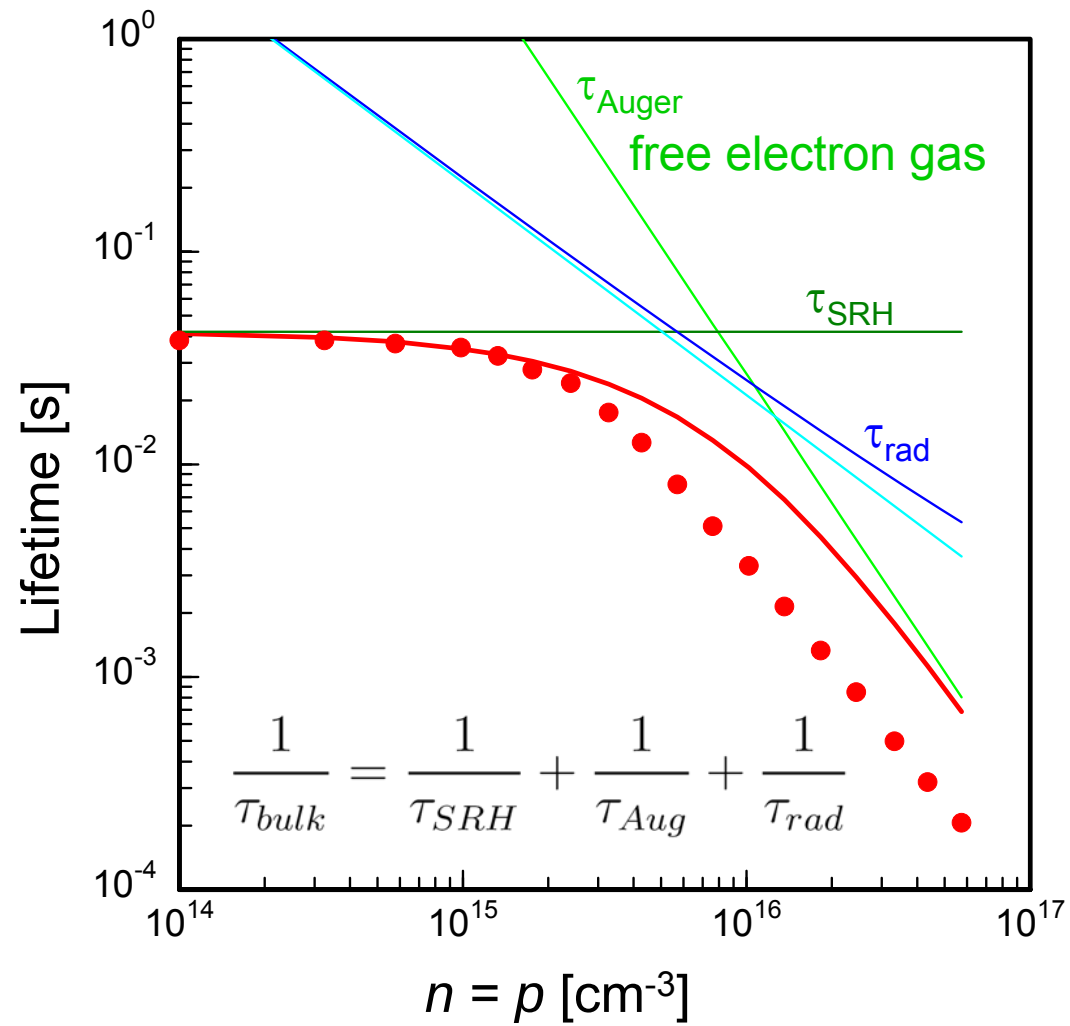
Experiment of Yablonovitch and Gmitter:



Simulations



Simulations



Simulations

Two short-comings:

1. Auger is Coulomb-enhanced like radiative
2. Photon-recycling (Si in HF)

Simulations

Photon-recycling

1) van Roosbroeck $\Rightarrow$ spontaneous radiation / volume:

$$dR_{sp}(E) = \frac{E^2 N^2}{\pi^2 \hbar^3 c_0^2} \alpha_{bb} \frac{1}{e^{(E-\Delta E_F)/kT} - 1} dE \quad \times d \quad / \text{wafer area}$$

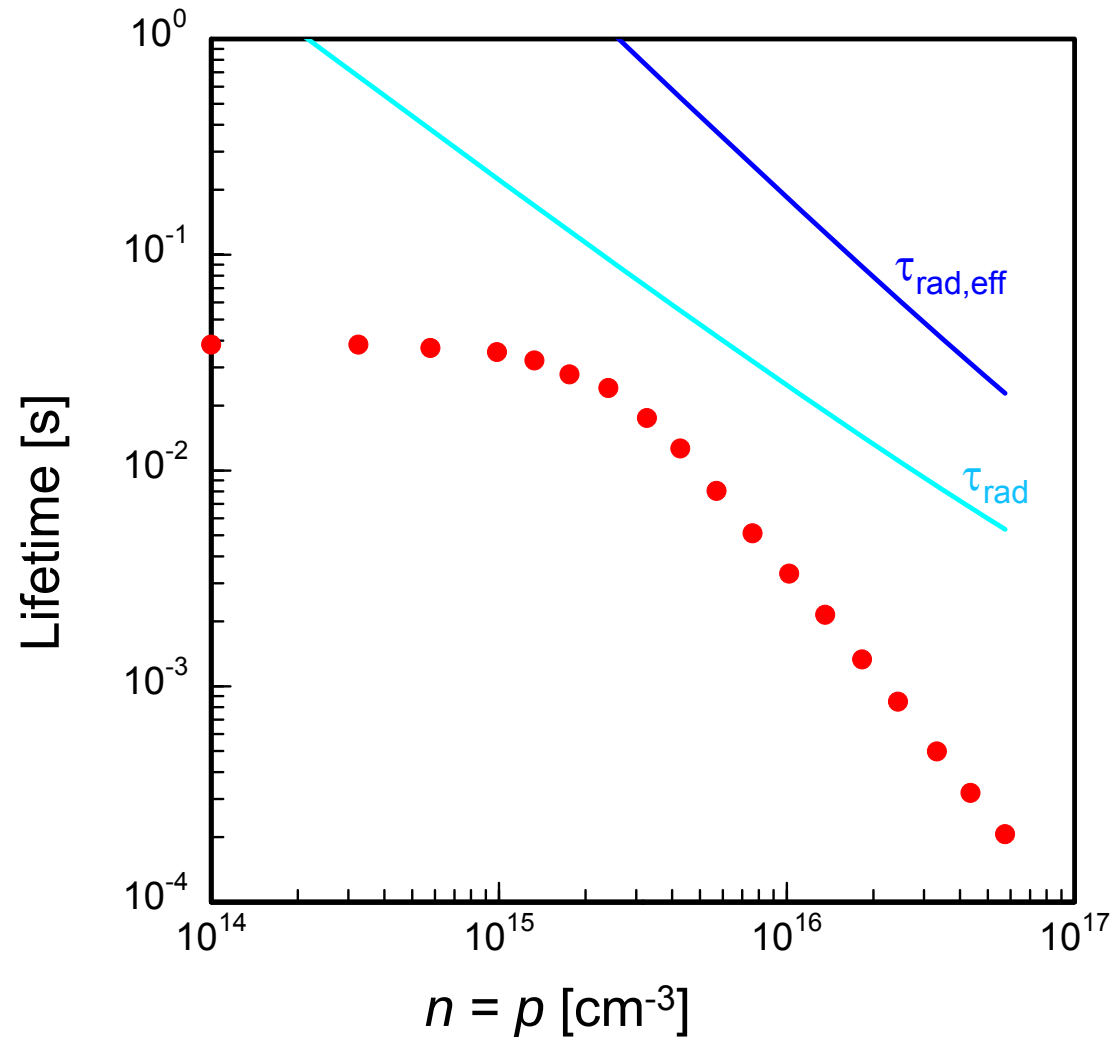
2) generalised Kirchhoff $\Rightarrow$ total external photon flux:

$$dj_{em}(E)dE = \frac{E^2}{4\pi^2 \hbar^3 c_0^2} \frac{\alpha_{bb}}{\alpha_{bb} + \alpha_{paras}} A \frac{1}{e^{(E-\Delta E_F)/kT} - 1} dE$$

1)+2) $\Rightarrow$ escape probability:

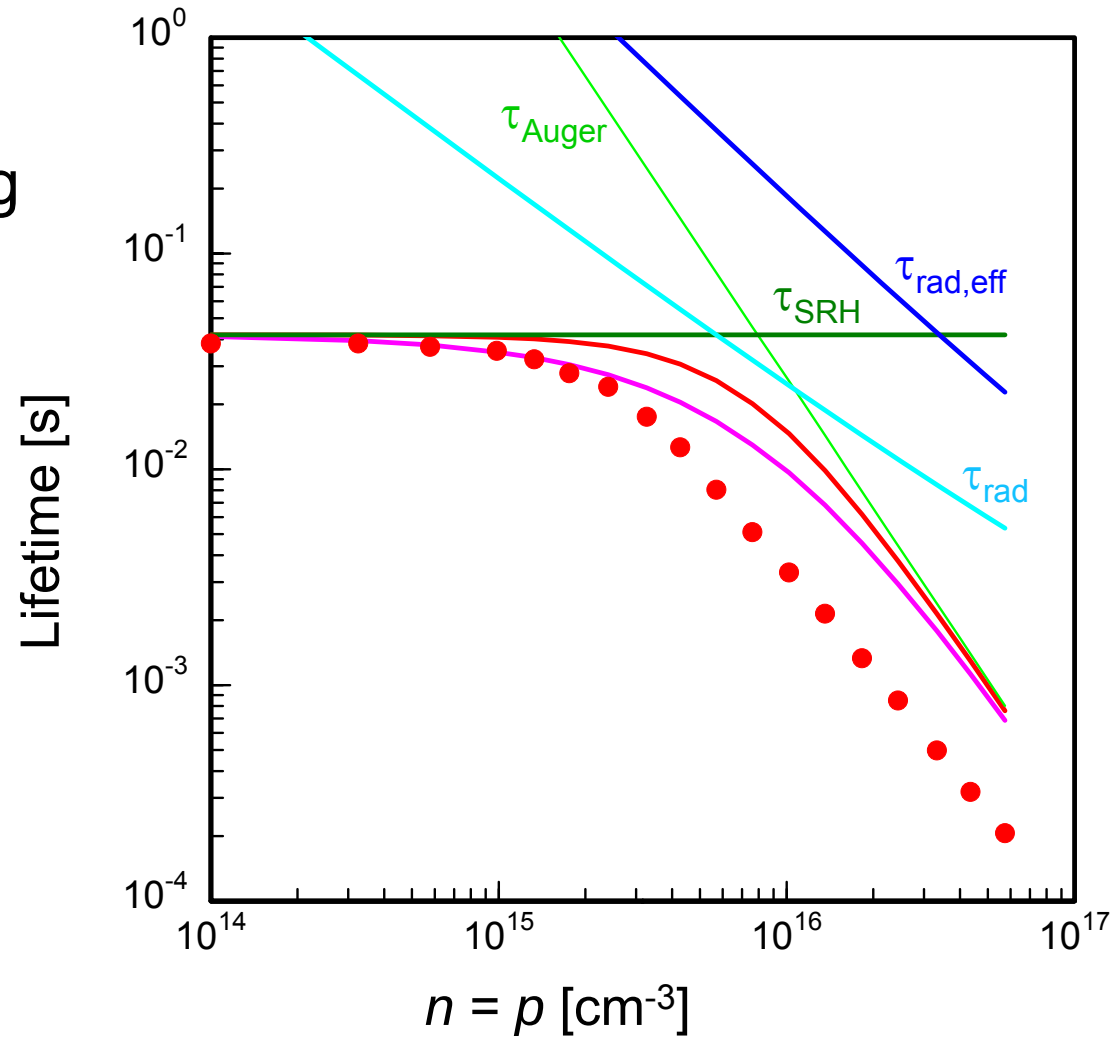
$$\eta_{esc,tot} = \frac{dj_{em}(E)}{d \cdot dR_{sp}(E)} = \frac{\int_0^\infty E^2 \frac{\alpha_{bb}}{\alpha_{bb} + \alpha_{paras}} A e^{(E-\Delta E_F)/kT} dE}{d \int_0^\infty 4E^2 N^2 \alpha_{bb} e^{(E-\Delta E_F)/kT} dE} = 3.42\%$$

Simulations



Simulations

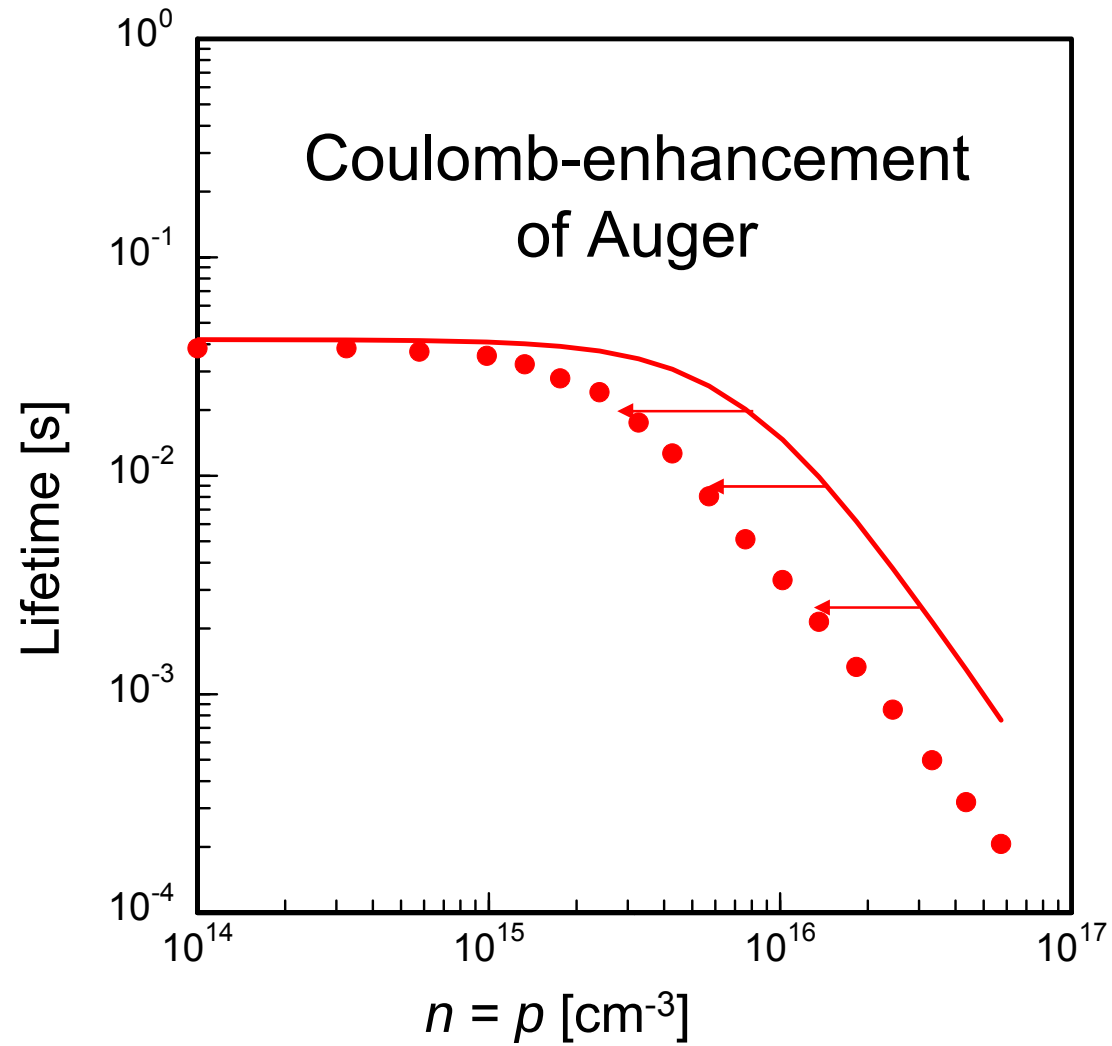
Will be a test
for forthcoming
Dessis 11



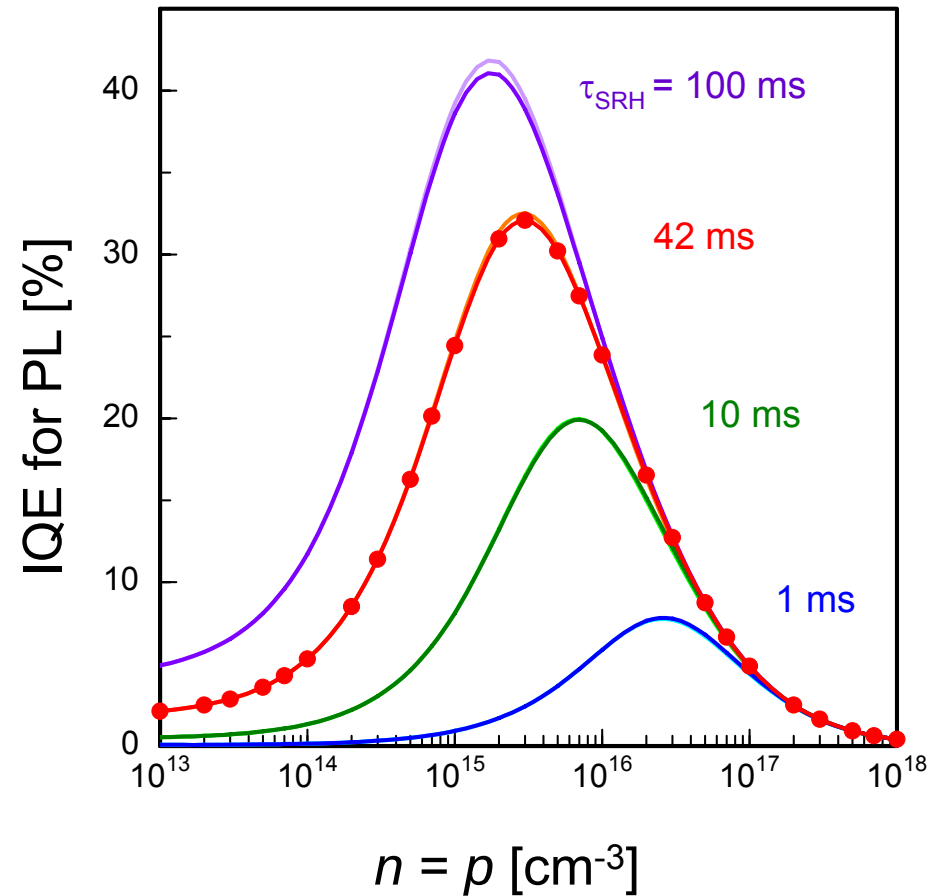
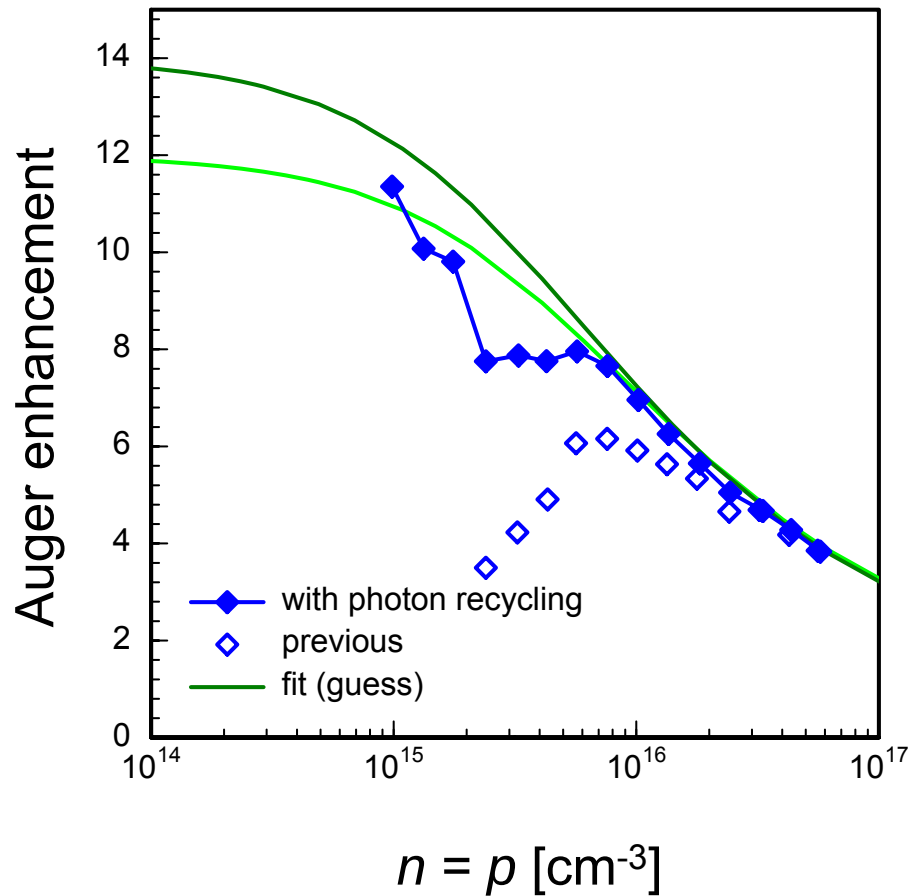
Outline

- Measurement of B
 - symmetrical plasma ($n=p$), method I
 - asymmetrical plasma ($n>p$, $n<p$), method II+III
- Calculation and parameterisation
- Simulation of a classic experiment
- Outlook

Outlook



Outlook



pietro@nano.uni-hannover.de

Thank you!