

# Amplified spontaneous and stimulated Mg L emission from MgO pumped by FEL pulses

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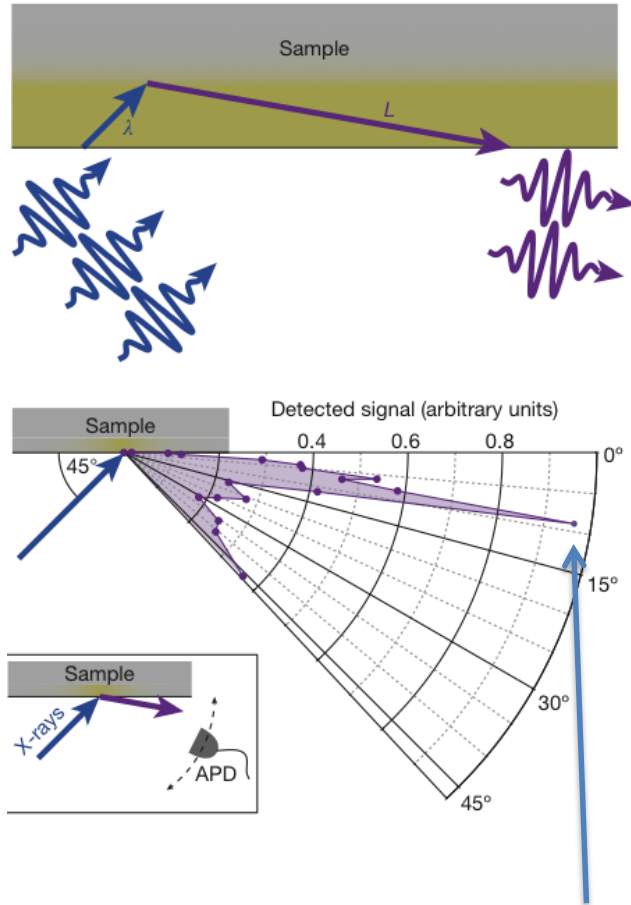
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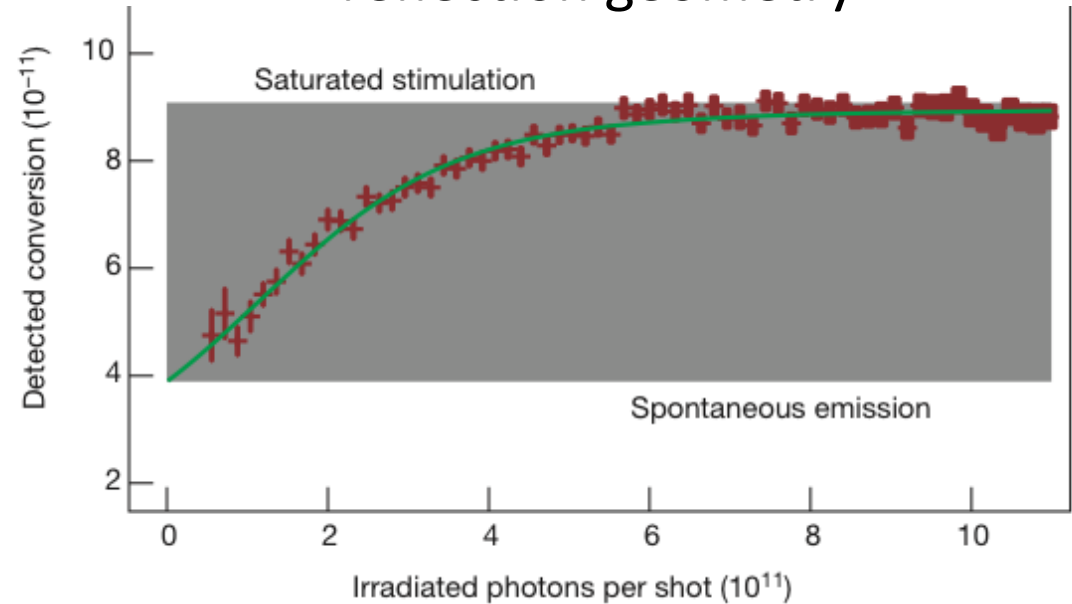


# Context: stimulated emission in the solid state

## Beye *et al.* experiment



**Si sample – Si  $L_{2,3}$  emission – 92 eV**  
reflection geometry



Emission in a **preferred direction**

**Saturation** of emitted intensity

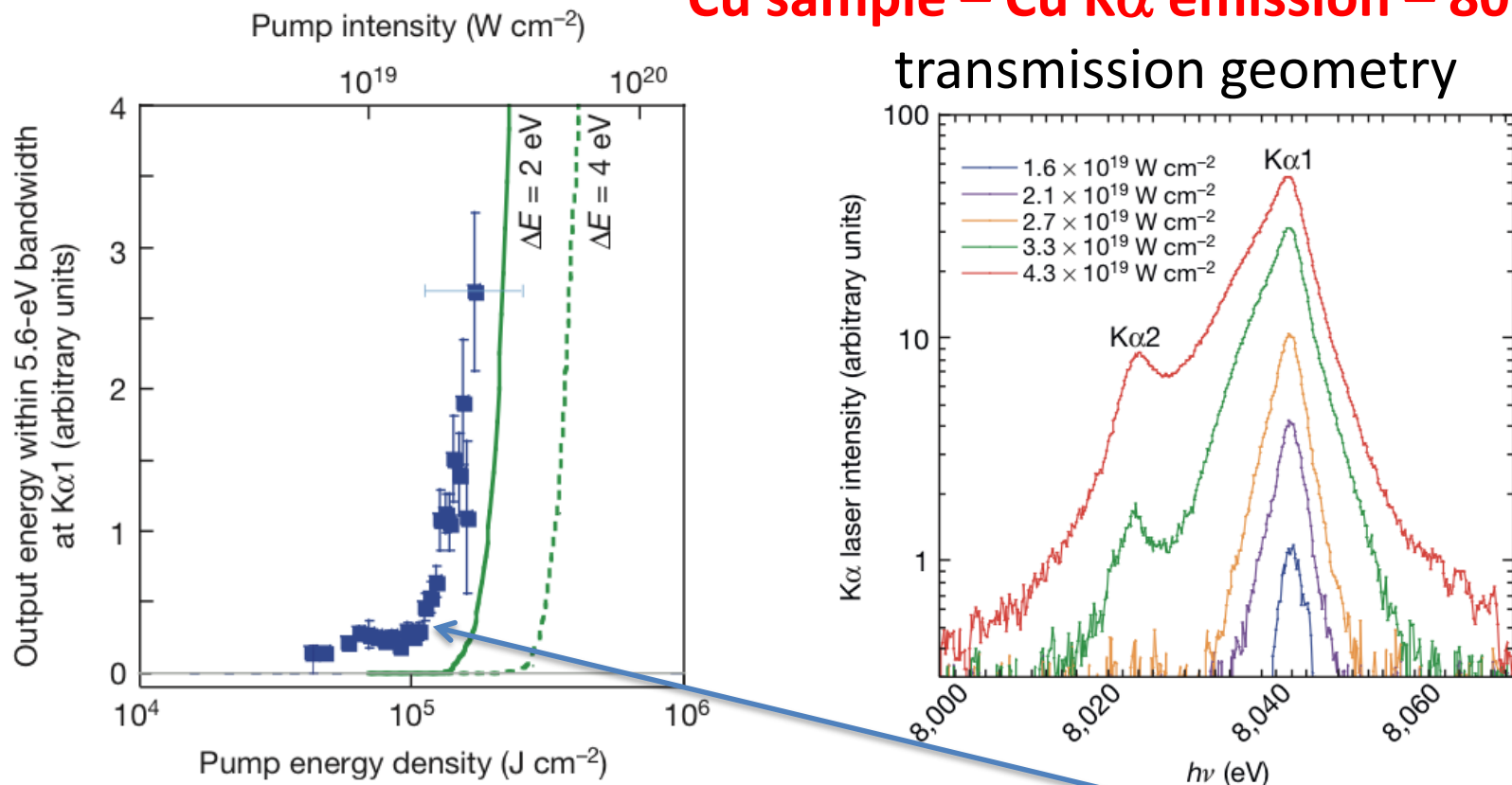


Signature of **stimulated emission**

# Context: stimulated emission in the solid state

## Yoneda *et al.* experiment

Cu sample – Cu K $\alpha$  emission – 8050 eV

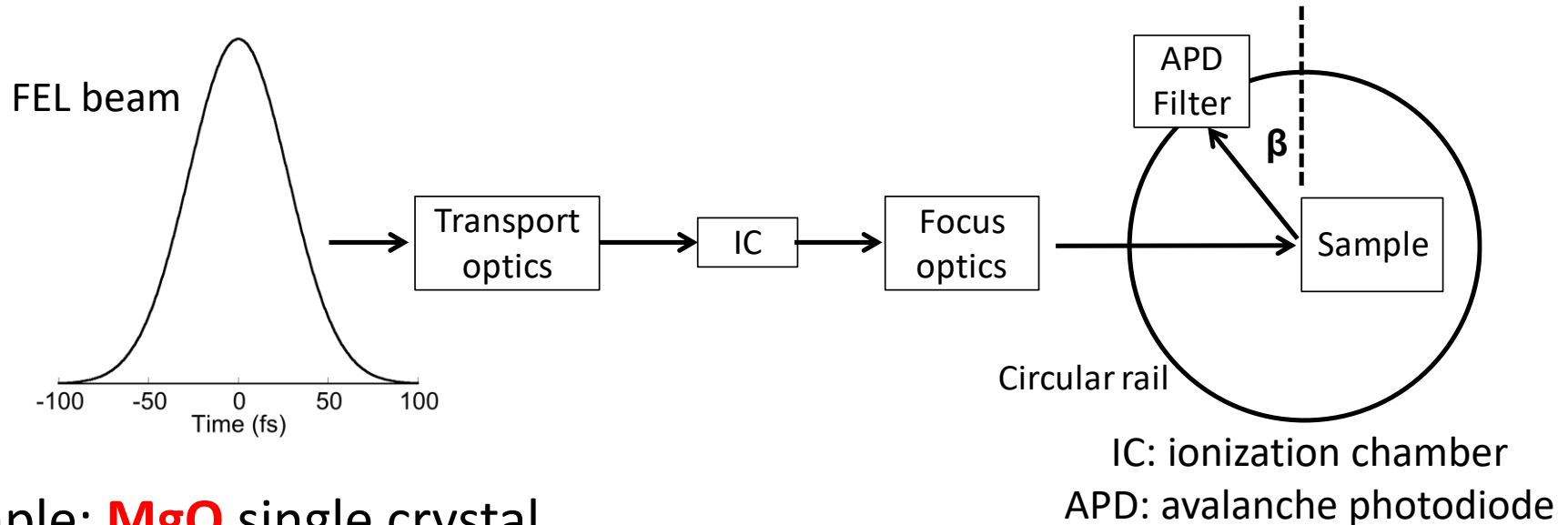


Nonlinear enhancement from a **pumping threshold**



Typical of lasing based on **amplified spontaneous emission** (ASE)

# Experimental setup



Sample: **MgO** single crystal

**Incident** FEL beam

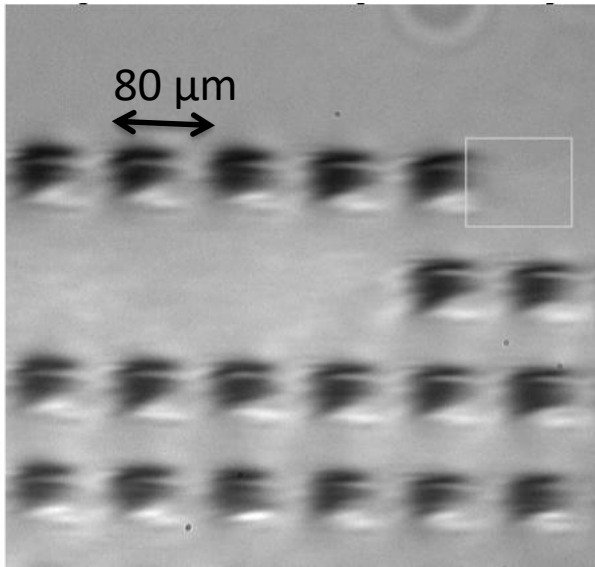
- **56.8 eV** (21.8 nm)
- **65 fs**
- **$10^{13}$  photons** /shot
- single shot

**Filter** cuts

- scattered incident beam
- visible light
- seeding laser

**Emitted** photon energy: **Mg L<sub>2,3</sub> emission band** ( $3sd-2p_{1/2,3/2}$  transition) centered around **45 eV**

# Single shot experiment



## Telemicroscope image

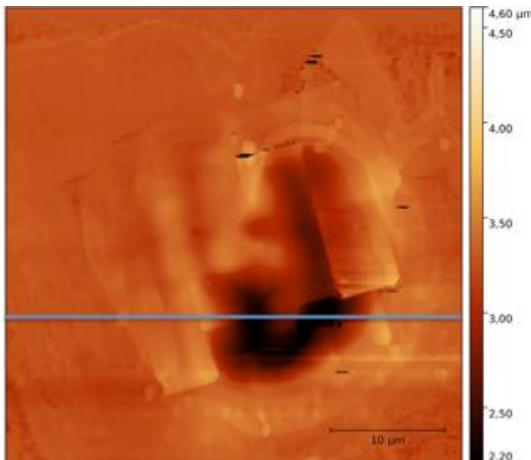
Sample damage

One shot (**65 fs**) – one intensity measurement

Time for **thermalisation**

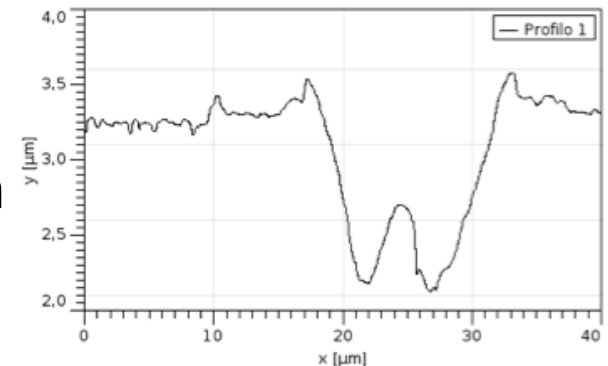
$10^{-10} - 10^{-11}$  s ( **$10^4 - 10^5$  fs**)

**Observation before damaging occurs**



## AFM image

Crater - width 15 μm  
- depth 2 μm

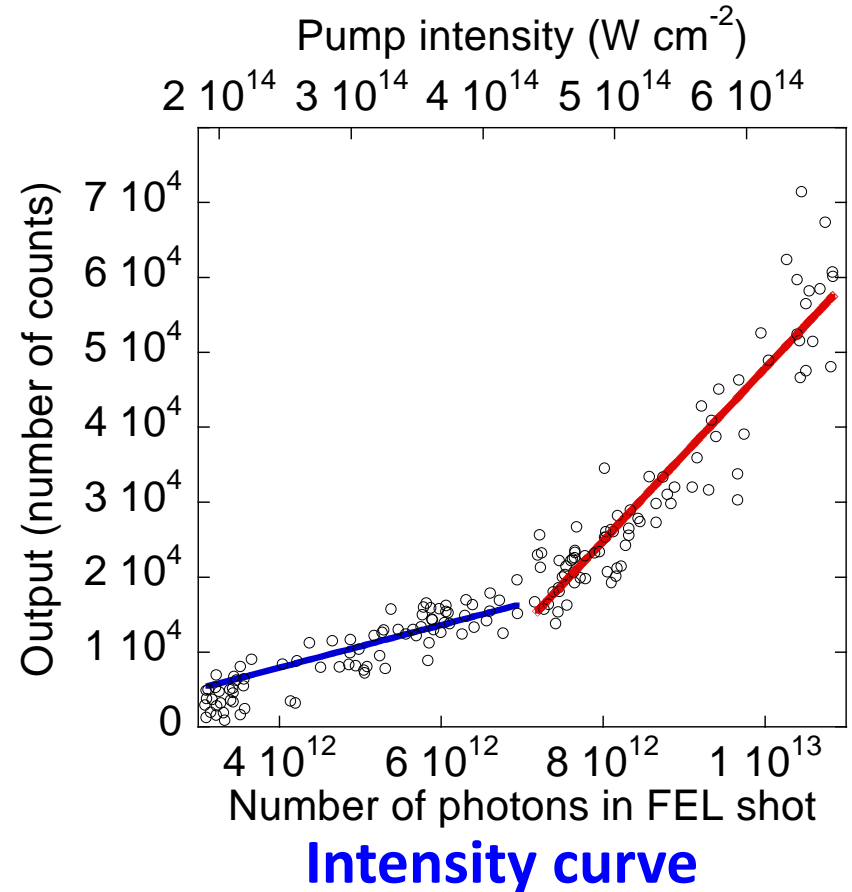
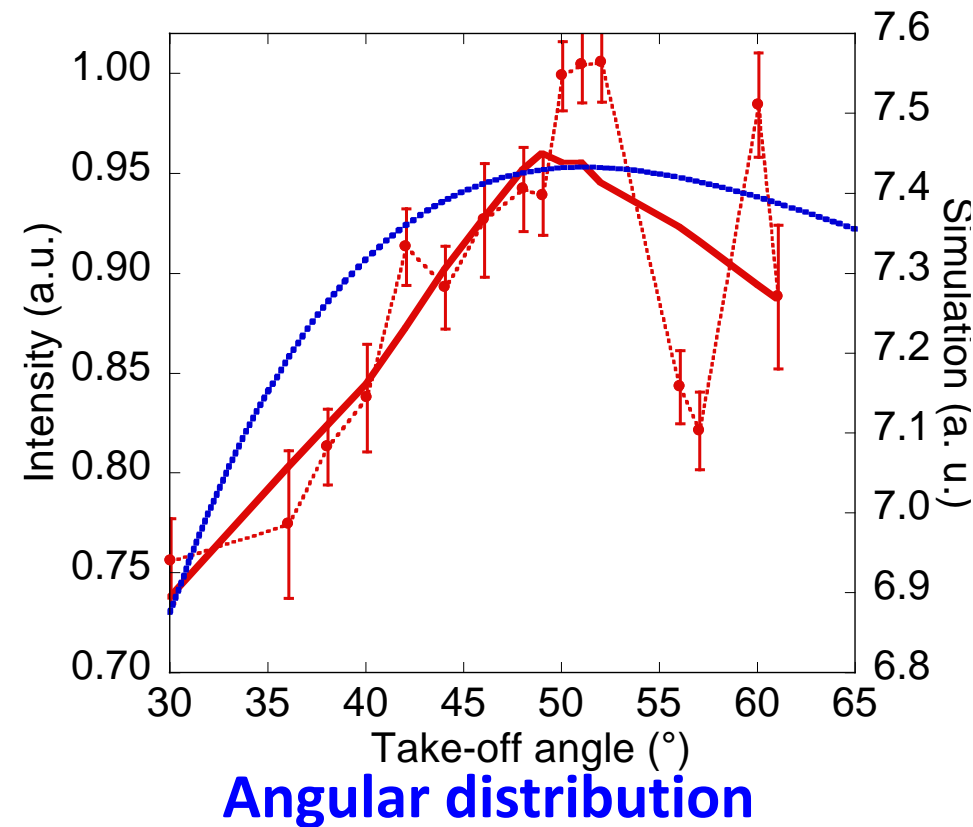


# Results

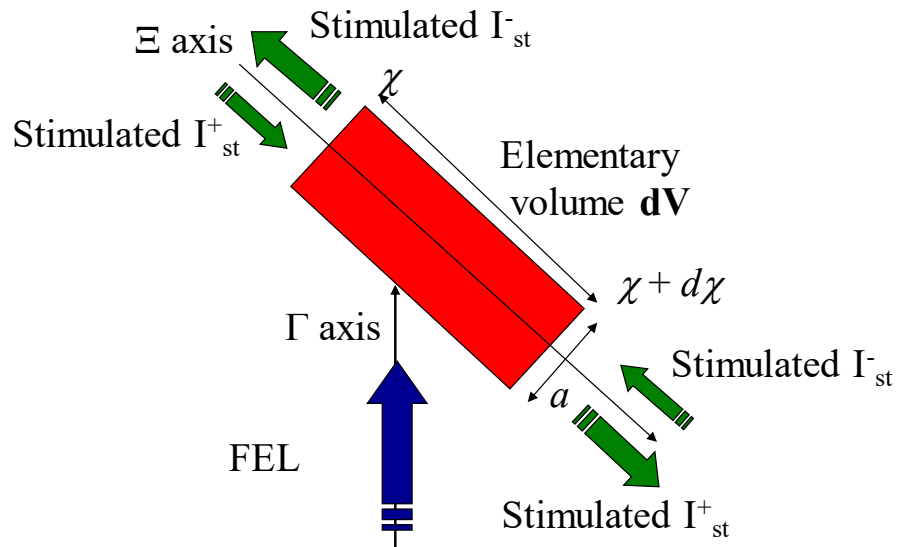
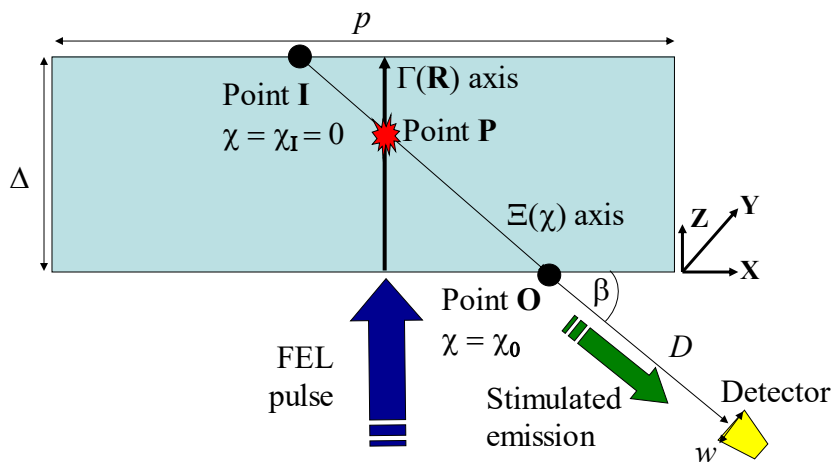
MgO sample; emission Mg L<sub>2,3</sub> @ 45 eV  
FEL excitation: 56.8 eV; 65 fs; single shot

≈95 μJ (10<sup>13</sup> photons)  
per shot

Detection angle 52°



# Model: rate equation



**rate equation:**

$\rho_c$  density of core holes

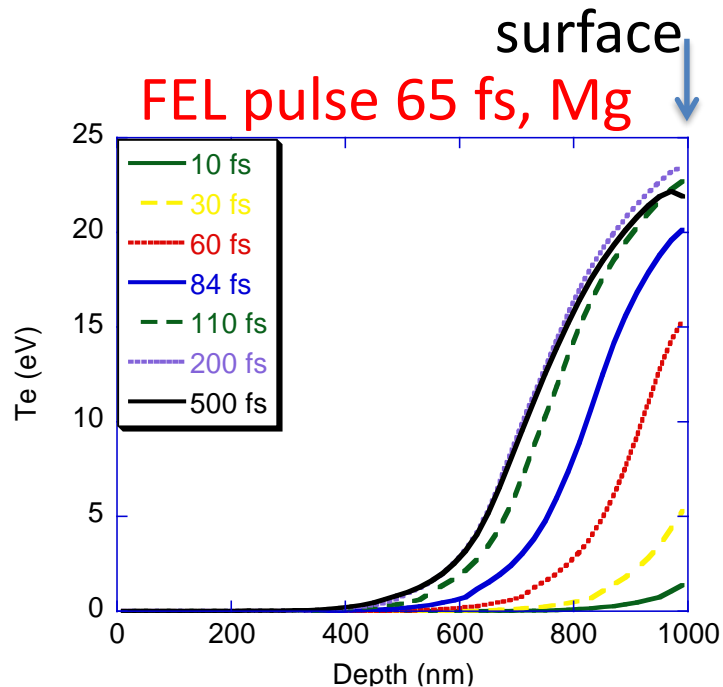
generated by the incident photon beam at a point  $\mathbf{P}$

$$\partial_t \rho_c(\mathbf{P}, t) = p (N(\mathbf{P}) - \rho_c(\mathbf{P}, t)) - \frac{\rho_c(\mathbf{P}, t)}{\tau_c} - r \rho_c(\mathbf{P}, t)$$

**Creation** by **ionization**    **Loss** by **spontaneous emission and Auger effect**    **Loss** by **stimulated emission**

$p$  photoionization rate,  $N$  concentration of atoms,  $r$  stimulated recombination rate,  $\tau_c$  phenomenological lifetime which may include possible collisional ionization effects

# Model: State of the sample under FEL exposure



Depth distribution of  
the electron temperature

Formation of a solid-density plasma

Quick change of the density of states

$p$  photoionization rate depends on  $\sigma_{ion}$ ,  $\phi(\mathbf{P}, t)$ ,  $P(\epsilon, T)$

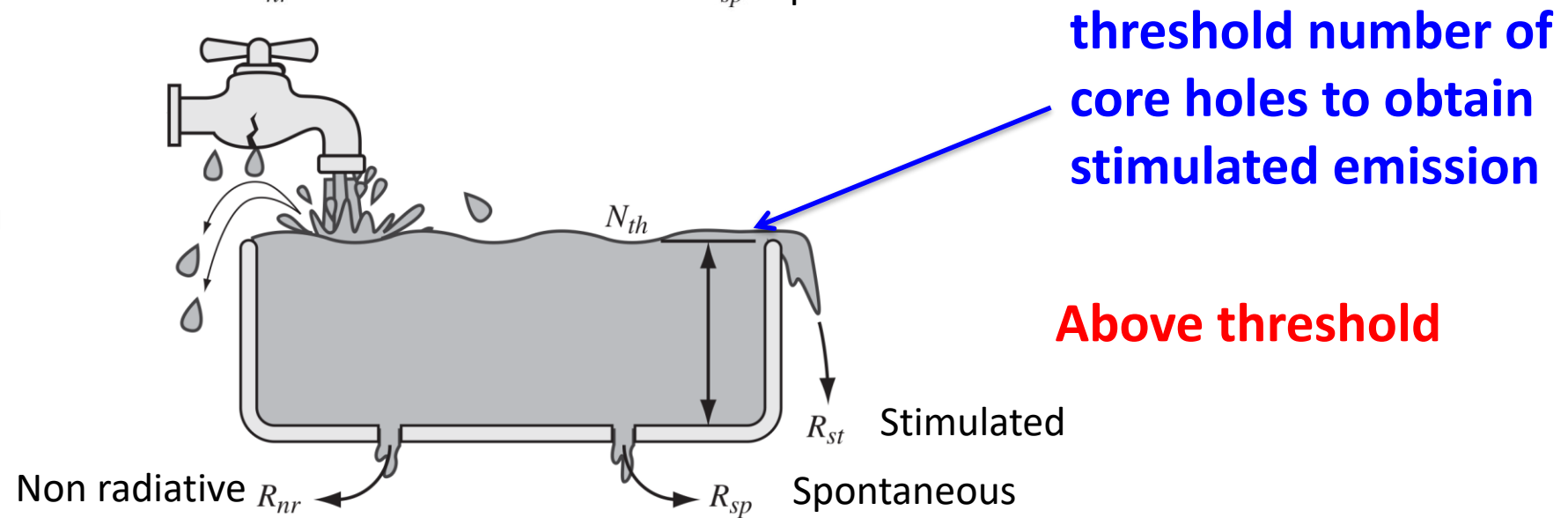
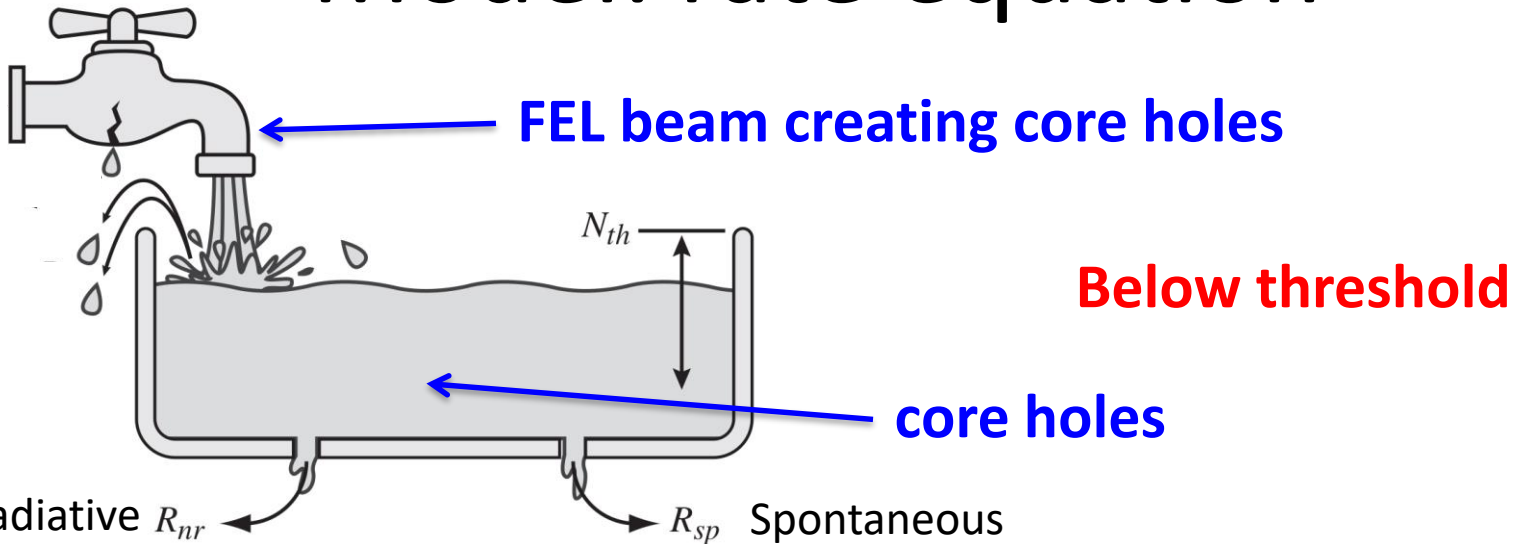
$r$  stimulated recombination rate depends on  $\sigma_{sti}$ ,  $I_{\Sigma}(\mathbf{P}, t)$ ,  $DOS$ ,  $FDS$

$\sigma_{ion}$  photoionization cross-section,  $\phi(\mathbf{P}, t)$  local FEL intensity,  $P(\epsilon, T)$  Pauli-blocking factor depending of the Fermi-Dirac statistics (FDS)

$\sigma_{sti}$  cross-section for stimulated effect,  $I_{\Sigma}(\mathbf{P}, t)$  spontaneous and stimulated intensities coming at  $\mathbf{P}$  from the whole volume  $\Sigma$ ,  $n_e$  electronic density, DOS density of states



# Model: rate equation



# Model: transport equation

Set of coupled differential equations governing the intensity growth

$$\pm \partial_{\chi} I^{\pm}(\chi) = \underbrace{\rho_c(\chi) \sigma_{st} \frac{I^{\pm}(\chi)}{1 + s I(\chi)}}_{\text{Growth and saturation term}} + \underbrace{\frac{F^{\pm}(\chi)}{T} \rho_c(\chi)}_{\text{Source term associated to spontaneous emission}} - \underbrace{\frac{I^{\pm}(\chi)}{L}}_{\text{Attenuation term}}$$

**Growth and saturation term**

**Source term** associated to **spontaneous emission**

**Attenuation term** mainly **photo-absorption**

$$I(\chi) = I^+(\chi) + I^-(\chi) \quad s = \sigma_{st} \tau_c$$

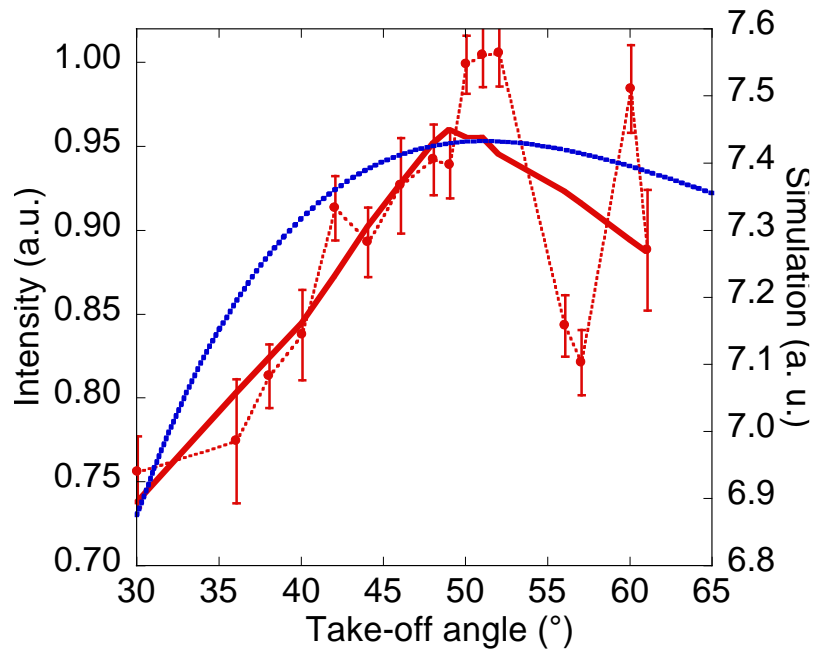
$$L = \frac{\Lambda}{\sin \beta}$$

$$T = \sqrt{\tau^2 + \tau_c^2}$$

$$F^{\pm}(\chi) = \omega_{sp} g^{\pm}(\chi)$$

$\rho_c$  density of core holes,  $\sigma_{st}$  stimulation cross-section,  $s$  saturation parameter,  $F$  fluorescence and geometry factor,  $T$  time constant governing the kinetics,  $L$  absorption length

# Comparisons



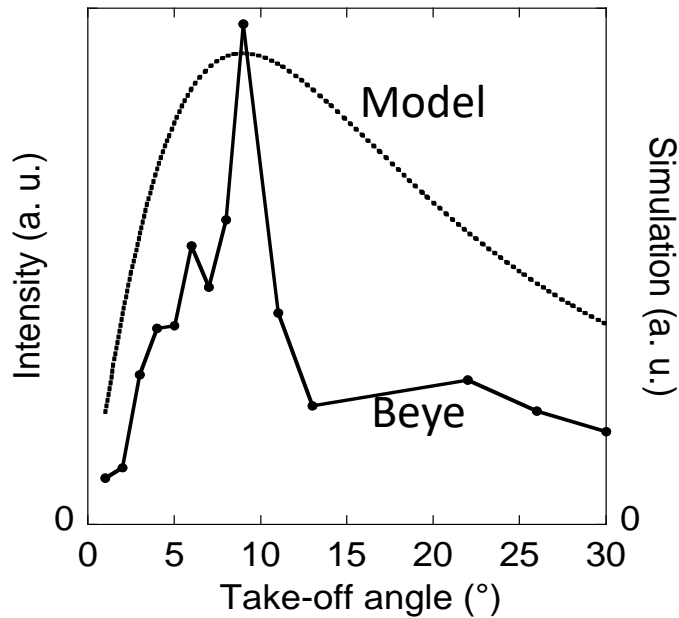
**Experiment**

**Simulation**

**Angular distribution**

**Preferred direction**

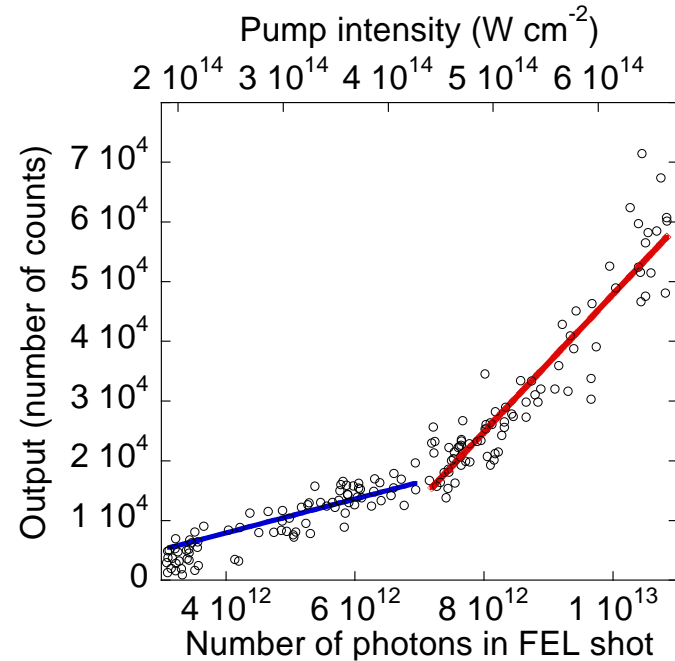
# Comparisons



**Angular distribution**

## Preferred direction

Beye's experiment  
Nature **501**, 191 (2013)



**Intensity curve**

## Pumping threshold

Model:  $5.1 \times 10^{14}\ W\ cm^{-2}$

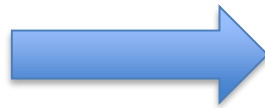
# Conclusion

## **EUV stimulated emission pumped by FEL pulses**

- from a solid target (MgO)
- in the regime of travelling-wave ASE
- in backward geometry

Model of

- **rate equation** and
- **transport** coupled **equations**



Experiment

- **directionality** and
- **pumping threshold**

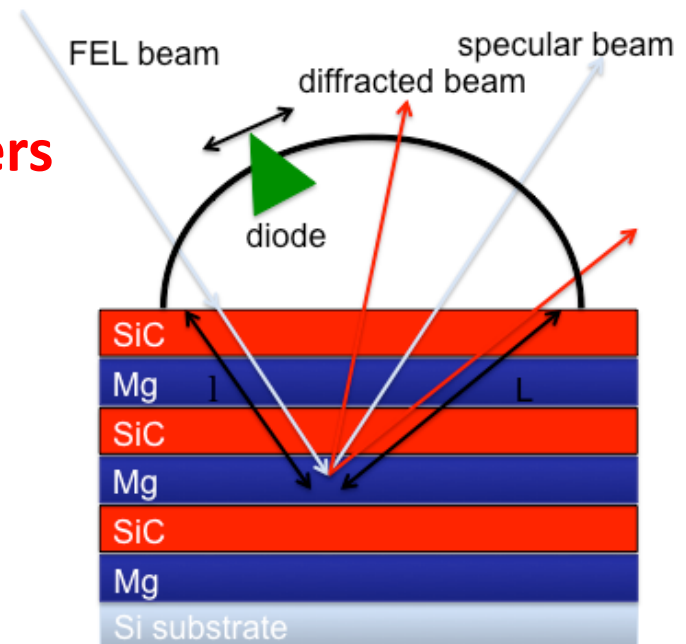
# Perspectives

**No optical feedback** → **Amplification** of the stimulated emission is **limited**

## **Distributed feedback (DFB) laser**

active medium = optical medium necessary for the feedback

- with **periodic nanometer multilayers** in the **EUV and soft x-ray ranges**
- with crystals in the **soft and hard x-ray ranges**



# Acknowledgments

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AFM measurements

Thank you