Near-field magneto-optical Microscopy

L. Alvarez-Prado[a], J. Schoenmaker[b], A.D. Santos[b],
Y. Souche[c]

[a] Departamento de Física, Universidad de Oviedo, Spain

[b] Laboratorio de Materiais Magnéticos, Inst. Física, Univ. São Paulo, Brazil

[c] Laboratoire Louis Néel, CNRS/ Univ. Joseph Fourier, Grenoble, France

X-tip / Grenoble / Novembre 17 2005

Outline

* Optical far-field, Rayleigh criterion and Near-field

* Some previous results

* Our experimental method

* Theoretical background

* The experimental set-up

* Some examples

Conclusions

Outline

* Optical far-field, Rayleigh criterion and Near-field

* Some previous results

* Our experimental method

* Theoretical background

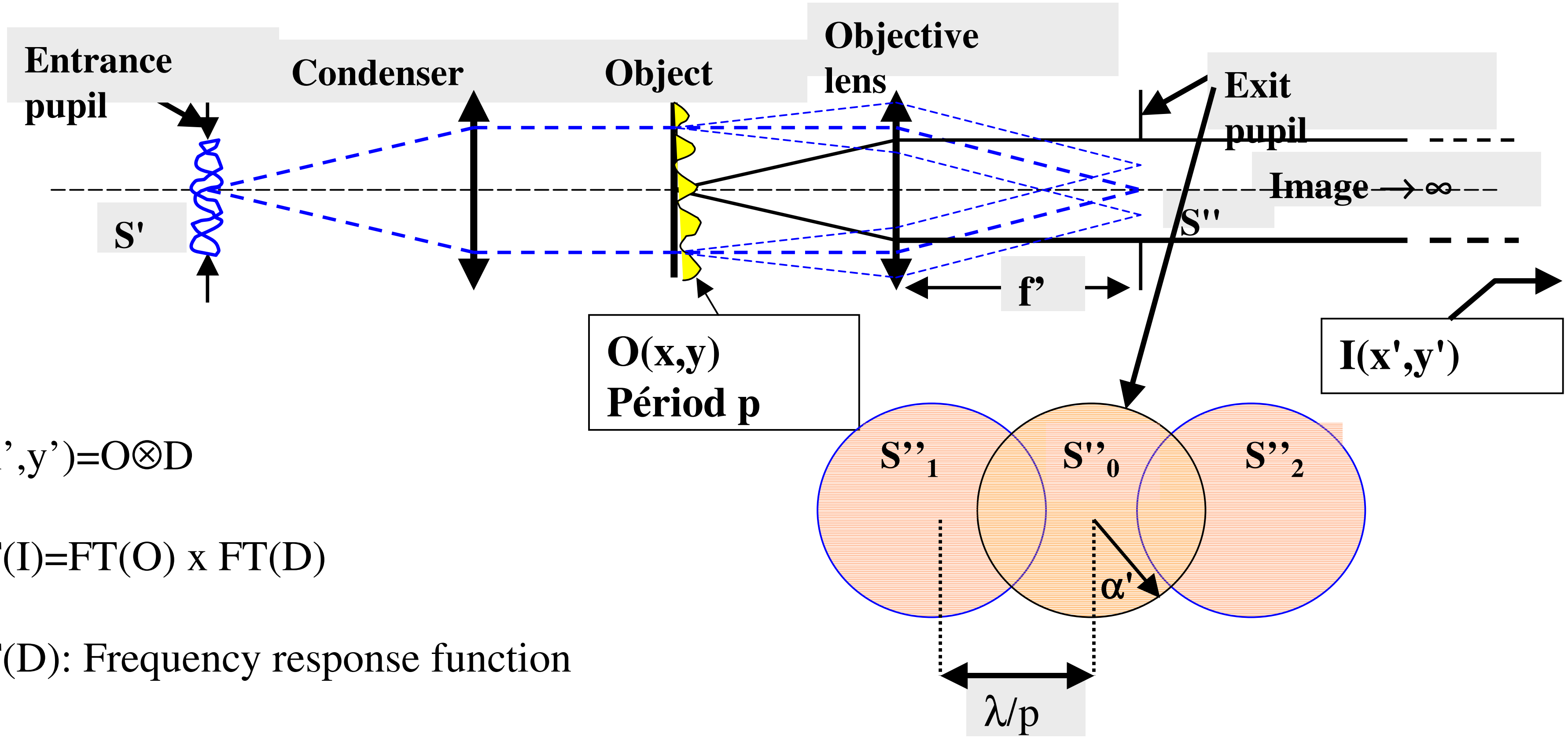
* The experimental set-up

* Some examples

Conclusions

Far-field optics

Object-image relation in incoherent light (Köhler illumination)



I(x',y')=O⊗D

FT(I)=FT(O) x FT(D)

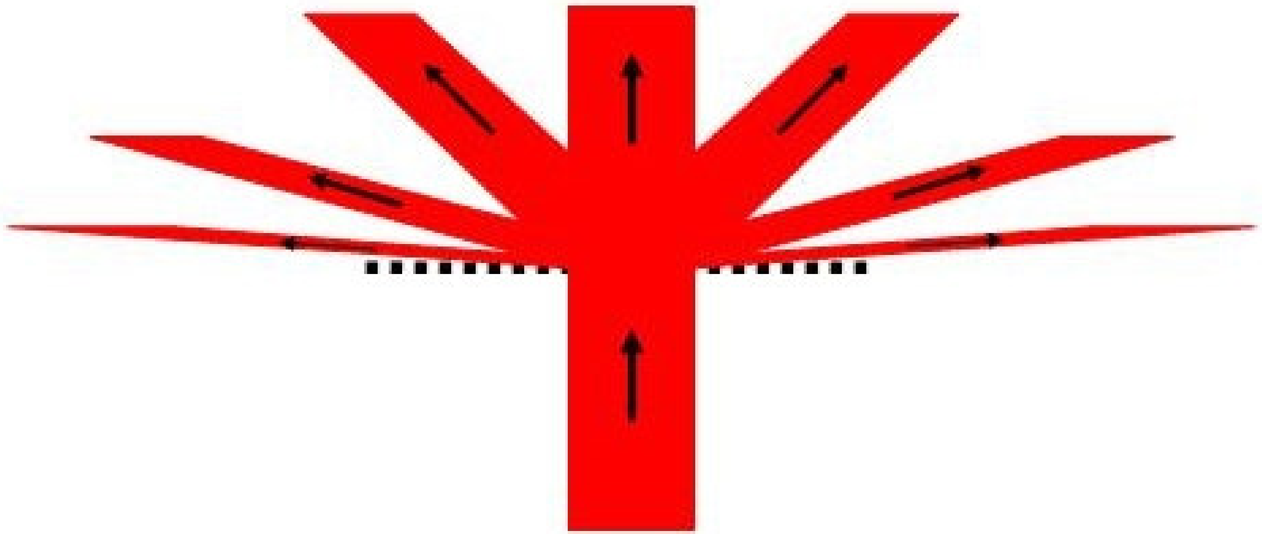
FT(D): Frequency response function

Rayleigh criterion => $2\alpha' = \lambda/p_{min}$

Minimum detectable Period

(α'=1)

$P_{min} \geq \lambda/2$



A light beam is diffracted by a periodic array

Only the propagating light is showed

Δs: uncertainty on measure of P position, s=(x,y)

Δk_s: uncertainty on measure of wave vector

Heisenberg relation:

$$\Delta s \cdot \Delta k_s \geq 2\pi$$

Rayleigh criterion: $\Delta s = \lambda/2$

$\Delta s < \lambda/2 \Rightarrow \Delta k_s > 4\pi/\lambda$

$k^2 = k_x^2 + k_y^2 + k_z^2 = (2\pi/\lambda)^2$

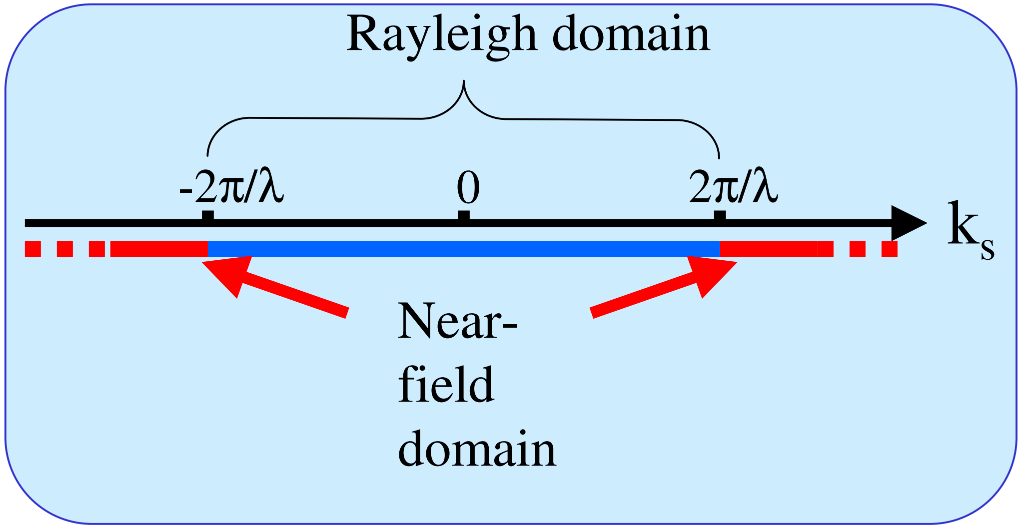
$k_x^2 + k_y^2 > (2\pi/\lambda)^2$

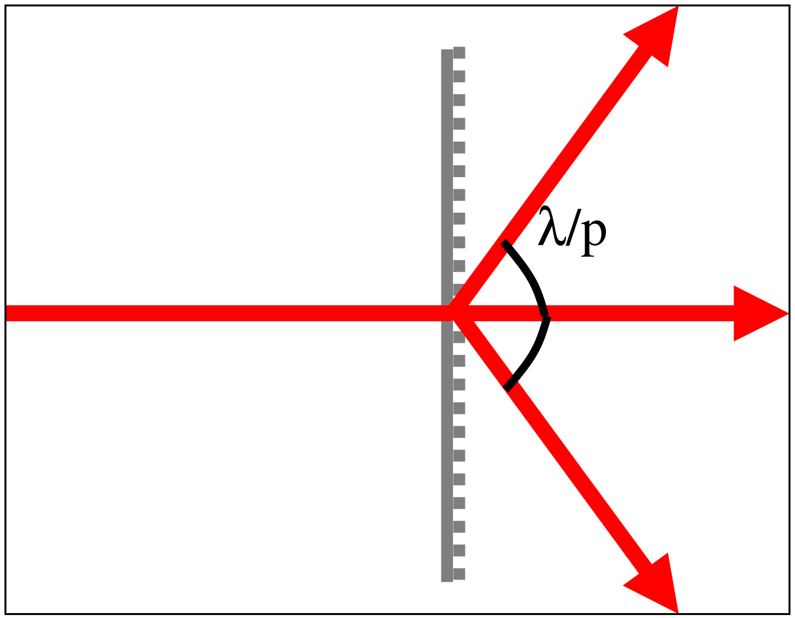
$\Rightarrow k_z^2 < 0$

$\mathbf{E} = \mathbf{E_0} \exp(-K_z z) \exp(j(\omega t - k_x x - k_y y))$

$k_z = jK_z$

evanescent waves





Δs: uncertainty on measure of P position

Δk_s: uncertainty on measure of wave vector

Heisenberg relation:

$$\Delta s . \Delta k_s \geq 2\pi$$

Rayleigh criterion: $\Delta s = \lambda/2$

$\Delta s < \lambda/2 \Rightarrow \Delta k_s > 4\pi/\lambda$

$k^2 = k_x^2 + k_y^2 + k_z^2 = (2\pi/\lambda)^2$

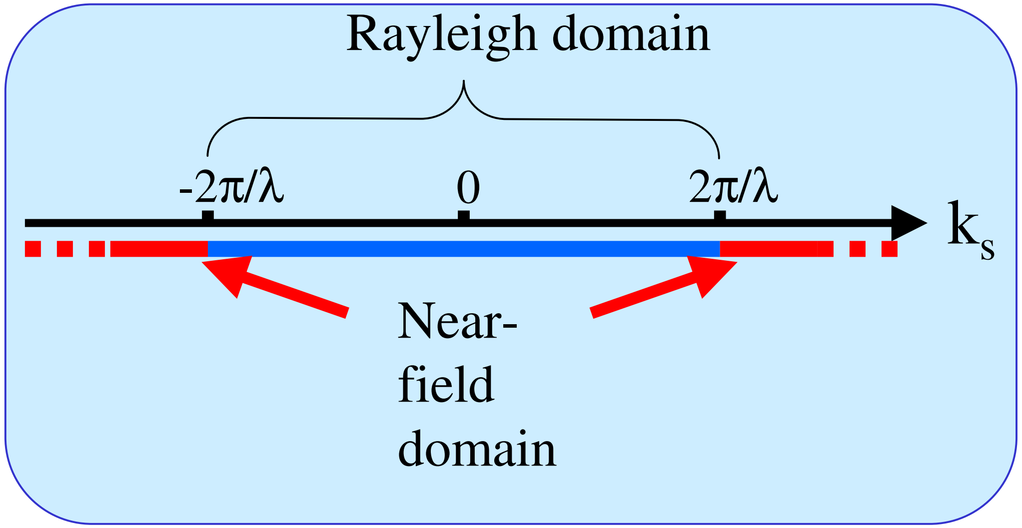
$k_x^2 + k_y^2 > (2\pi/\lambda)^2$

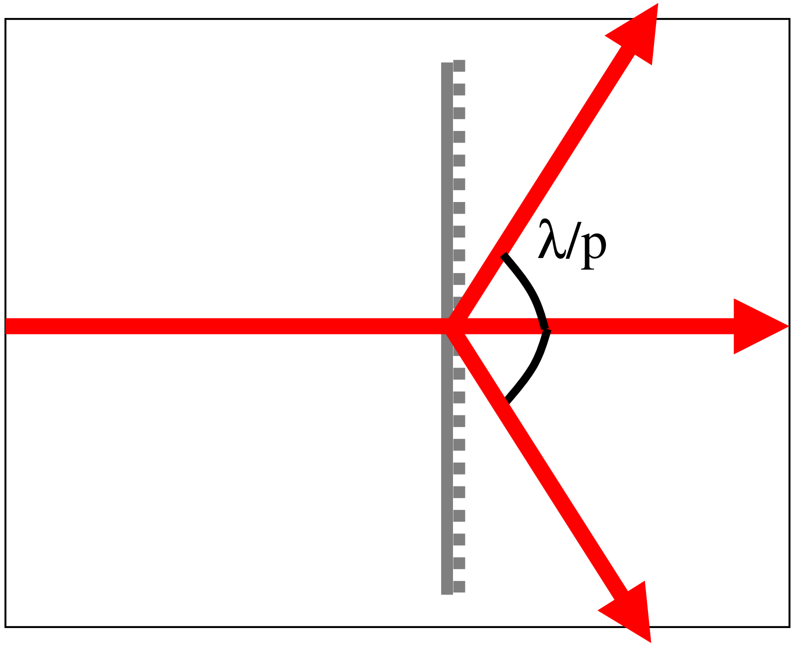
$\Rightarrow k_z^2 < 0$

$E = E_0 \exp(-K_z z) \exp(j(\omega t - k_x x - k_y y))$

$k_z = jK_z$

evanescent waves





Δs: uncertainty on measure of P position

Δk_s: uncertainty on measure of wave vector

Heisenberg relation:

$$\Delta s . \Delta k_s \geq 2\pi$$

Rayleigh criterion: $\Delta s = \lambda/2$

$\Delta s < \lambda/2 \Rightarrow \Delta k_s > 4\pi/\lambda$

$k^2 = k_x^2 + k_y^2 + k_z^2 = (2\pi/\lambda)^2$

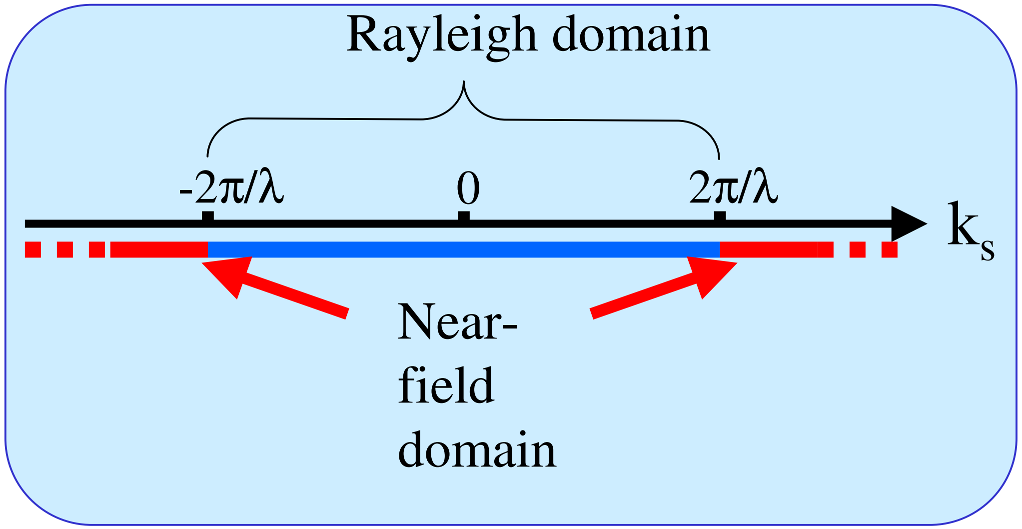
$k_x^2 + k_y^2 > (2\pi/\lambda)^2$

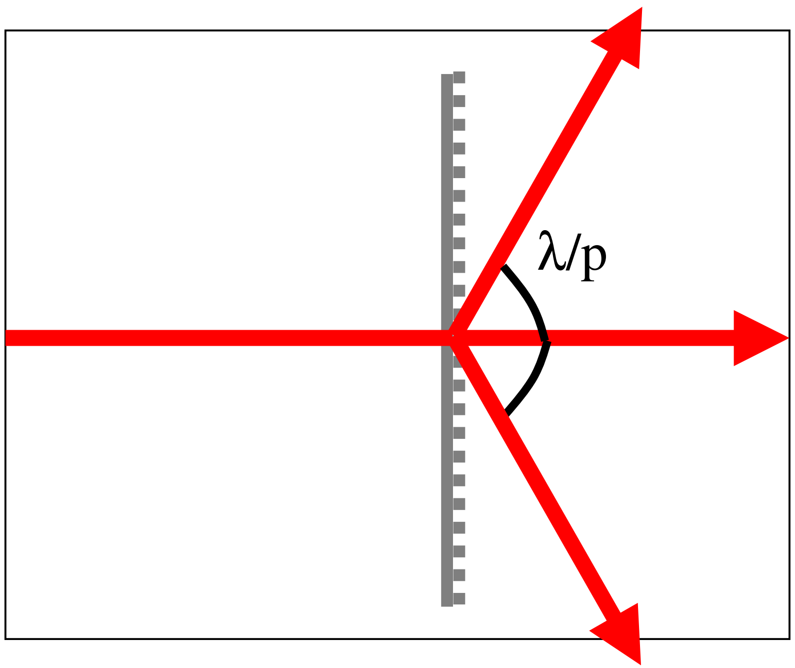
$\Rightarrow k_z^2 < 0$

$\mathbf{E} = \mathbf{E_0} \exp(-K_z z) \exp(j(\omega t - k_x x - k_y y))$

$k_z = jK_z$

evanescent waves





Δs: uncertainty on measure of P position

Δk_s: uncertainty on measure of wave vector

Heisenberg relation:

$$\mathbf{\Delta s . \Delta k_s \geq 2\pi}$$

Rayleigh criterion: $\Delta s = \lambda/2$

$\Delta s < \lambda/2 \Rightarrow \Delta k_s > 4\pi/\lambda$

$k^2 = k_x^2 + k_y^2 + k_z^2 = (2\pi/\lambda)^2$

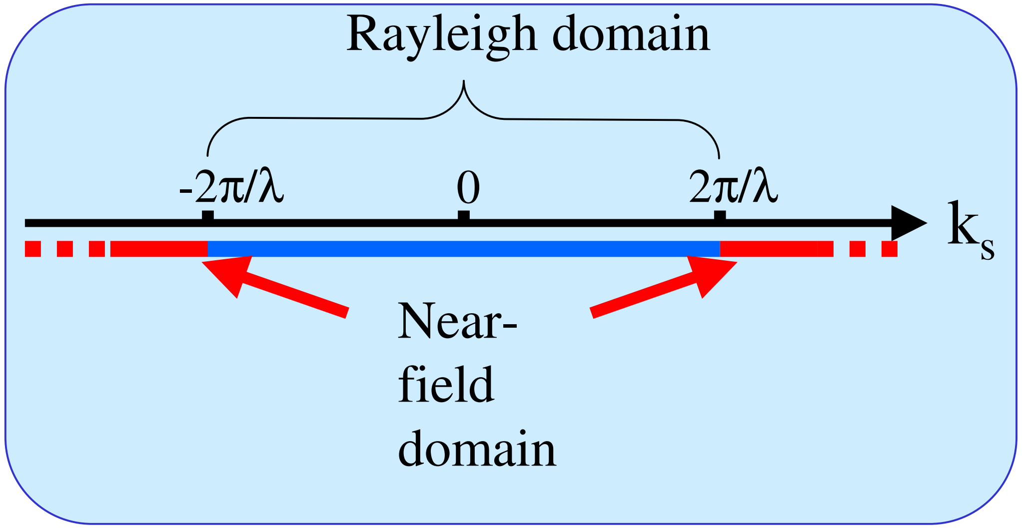
$k_x^2 + k_y^2 > (2\pi/\lambda)^2$

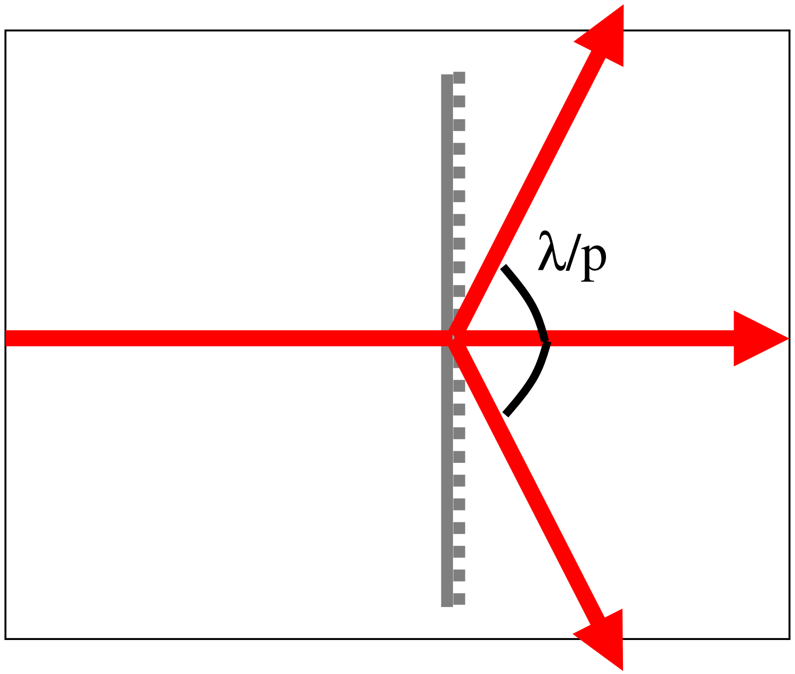
$\Rightarrow k_z^2 < 0$

$\mathbf{E} = \mathbf{E_0} \exp(-K_z z) \exp(j(\omega t - k_x x - k_y y))$

$k_z = jK_z$

evanescent waves





Δs: uncertainty on measure of P position

Δk_s: uncertainty on measure of wave vector

Heisenberg relation:

$$\Delta s . \Delta k_s \geq 2\pi$$

Rayleigh criterion: $\Delta s = \lambda/2$

$\Delta s < \lambda/2 \Rightarrow \Delta k_s > 4\pi/\lambda$

$k^2 = k_x^2 + k_y^2 + k_z^2 = (2\pi/\lambda)^2$

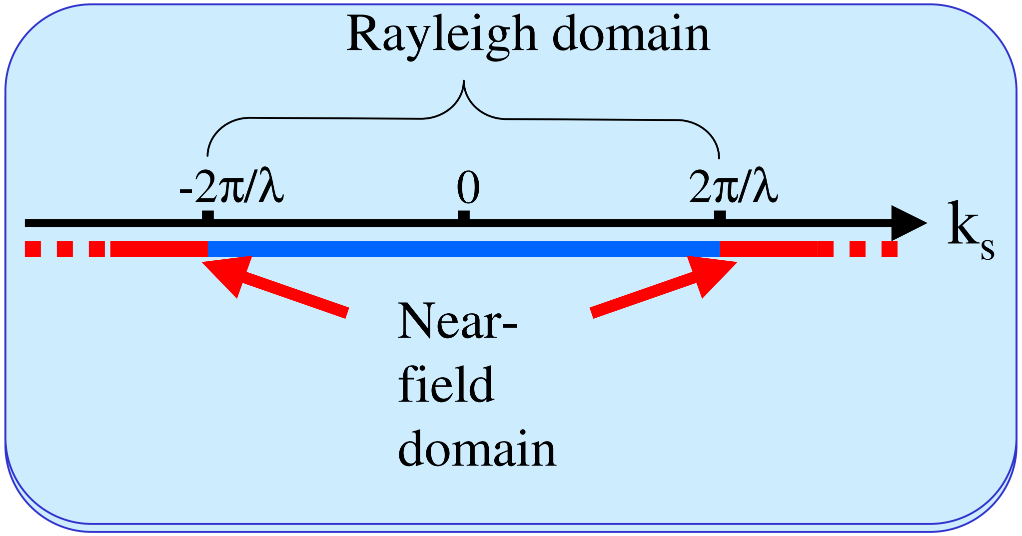
$k_x^2 + k_y^2 > (2\pi/\lambda)^2$

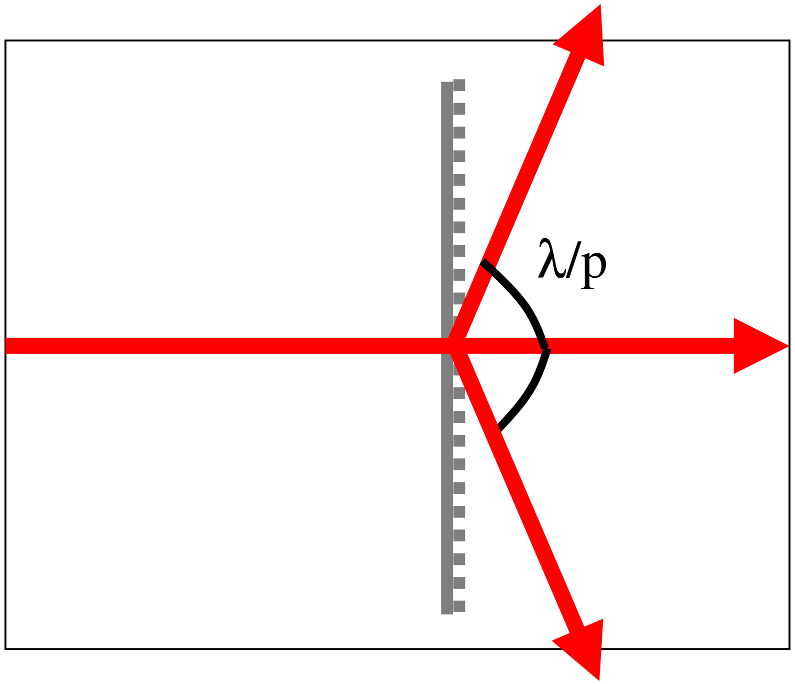
$\Rightarrow k_z^2 < 0$

$\mathbf{E} = \mathbf{E_0} \exp(-K_z z) \exp(j(\omega t - k_x x - k_y y))$

$k_z = jK_z$

evanescent waves





Δs: uncertainty on measure of P position

Δk_s: uncertainty on measure of wave vector

Heisenberg relation:

$$\Delta s . \Delta k_s \geq 2\pi$$

Rayleigh criterion: $\Delta s = \lambda/2$

$\Delta s < \lambda/2 \Rightarrow \Delta k_s > 4\pi/\lambda$

$k^2 = k_x^2 + k_y^2 + k_z^2 = (2\pi/\lambda)^2$

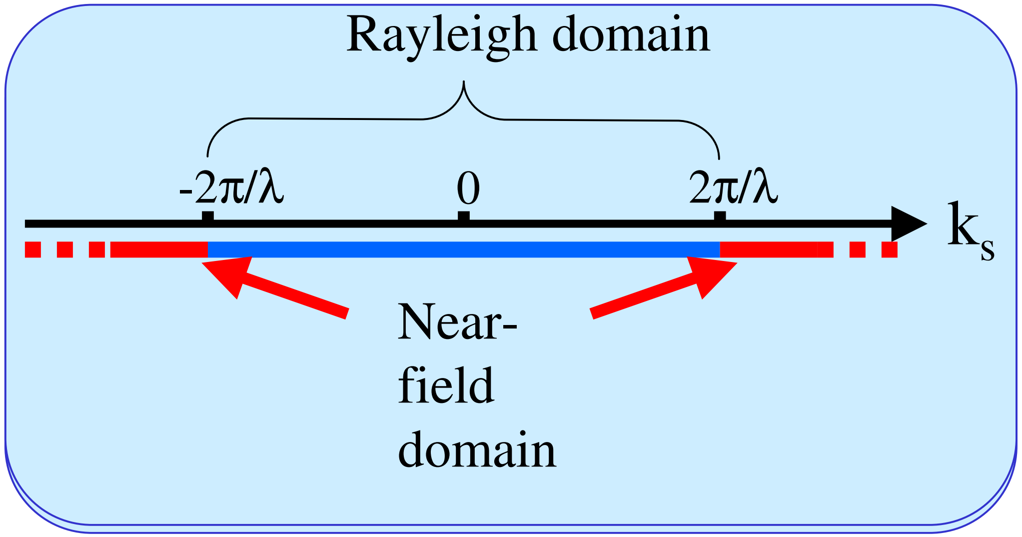
$k_x^2 + k_y^2 > (2\pi/\lambda)^2$

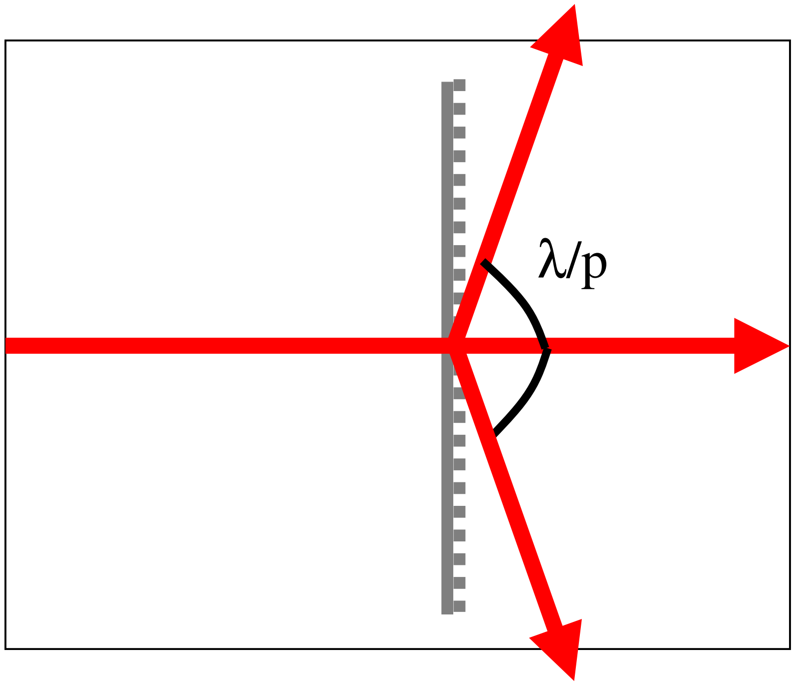
$\Rightarrow k_z^2 < 0$

$\mathbf{E} = \mathbf{E_0} \exp(-K_z\, z) \exp(j(\omega t - k_x x - k_y y)$

$k_z = jK_z$

evanescent waves





Δs: uncertainty on measure of P position

Δk_s: uncertainty on measure of wave vector

Heisenberg relation:

$$\Delta s . \Delta k_s \geq 2\pi$$

Rayleigh criterion: $\Delta s = \lambda/2$

$\Delta s < \lambda/2 \Rightarrow \Delta k_s > 4\pi/\lambda$

$k^2 = k_x^2 + k_y^2 + k_z^2 = (2\pi/\lambda)^2$

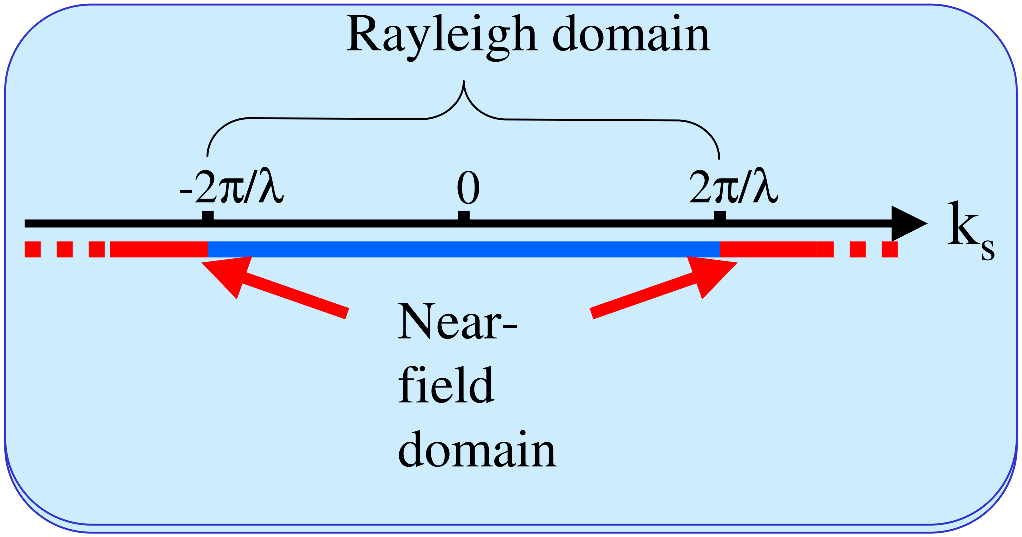
$k_x^2 + k_y^2 > (2\pi/\lambda)^2$

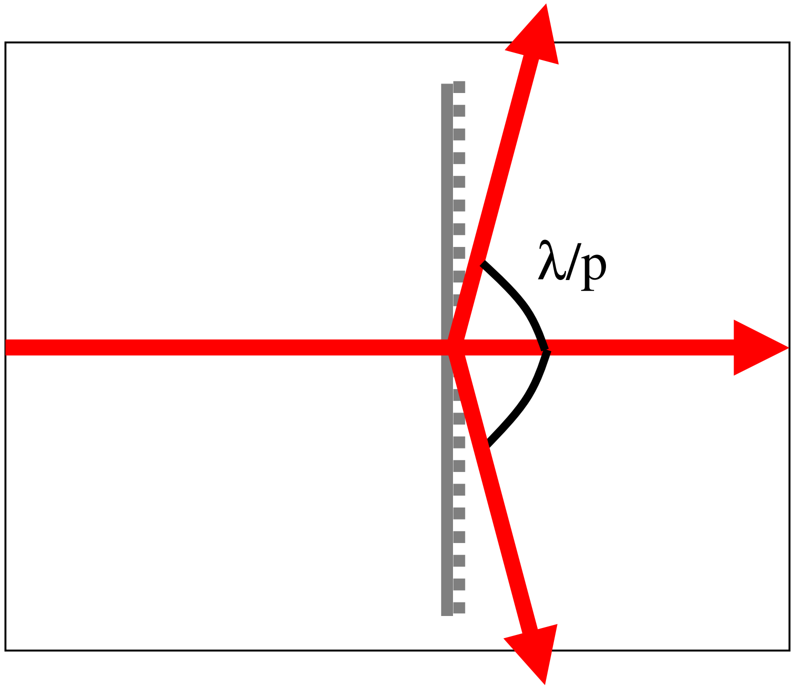
$\Rightarrow k_z^2 < 0$

$\mathbf{E} = \mathbf{E_0} \exp(-K_z z) \exp(j(\omega t - k_x x - k_y y))$

$k_z = jK_z$

evanescent waves





Δs: uncertainty on measure of P position

Δk_s: uncertainty on measure of wave vector

> Heisenberg relation:
>
> $$\Delta s.\Delta k_s \geq 2\pi$$

Rayleigh criterion: $\Delta s = \lambda/2$

$\Delta s < \lambda/2 \Rightarrow \Delta k_s > 4\pi/\lambda$

$k^2 = k_x^2 + k_y^2 + k_z^2 = (2\pi/\lambda)^2$

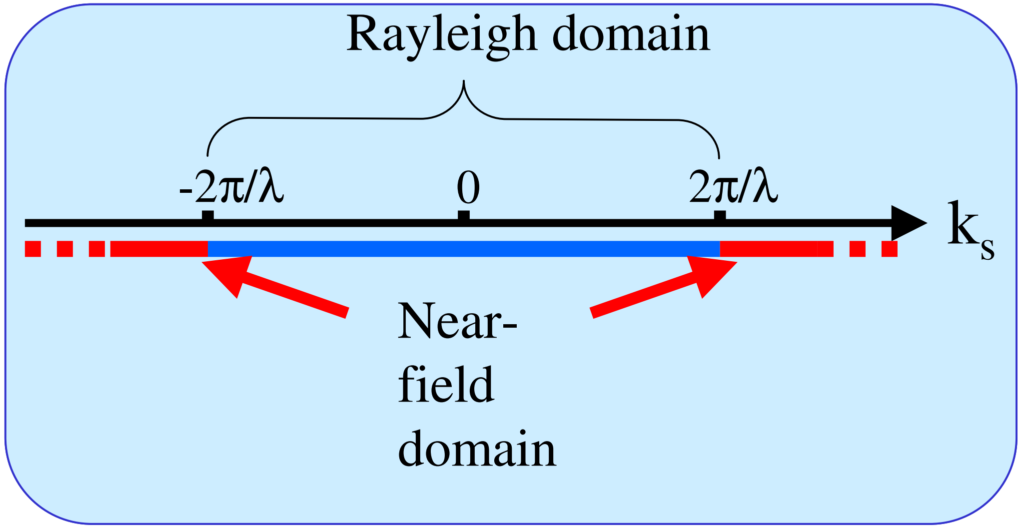
$k_x^2 + k_y^2 > (2\pi/\lambda)^2$

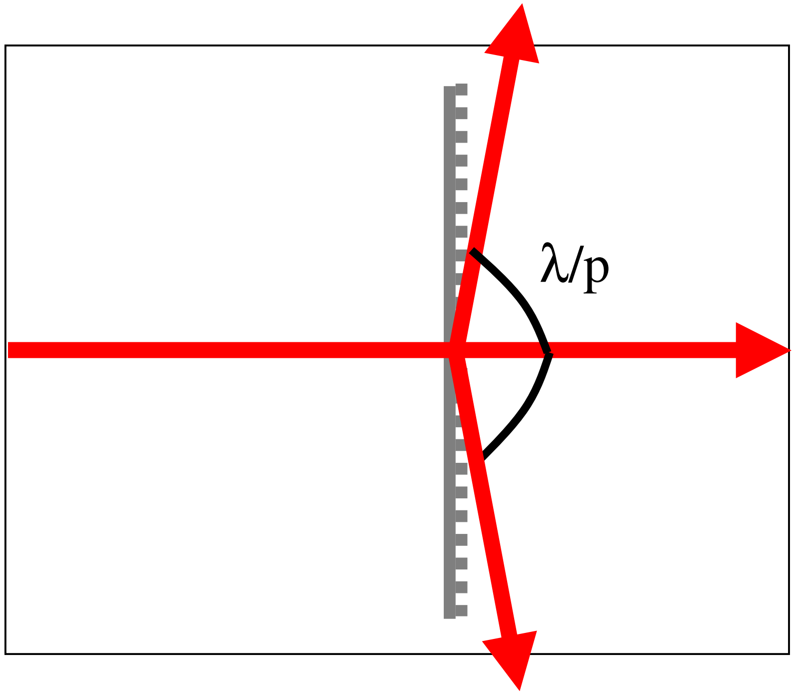
$\Rightarrow k_z^2 < 0$

$\mathbf{E} = \mathbf{E_0} \exp(-K_z z) \exp(j(\omega t - k_x x - k_y y))$

$k_z = jK_z$

evanescent waves





Δs: uncertainty on measure of P position
Δk_s: uncertainty on measure of wave vector

Heisenberg relation:

$$\Delta s . \Delta k_s \geq 2\pi$$

Rayleigh criterion: $\Delta s = \lambda/2$

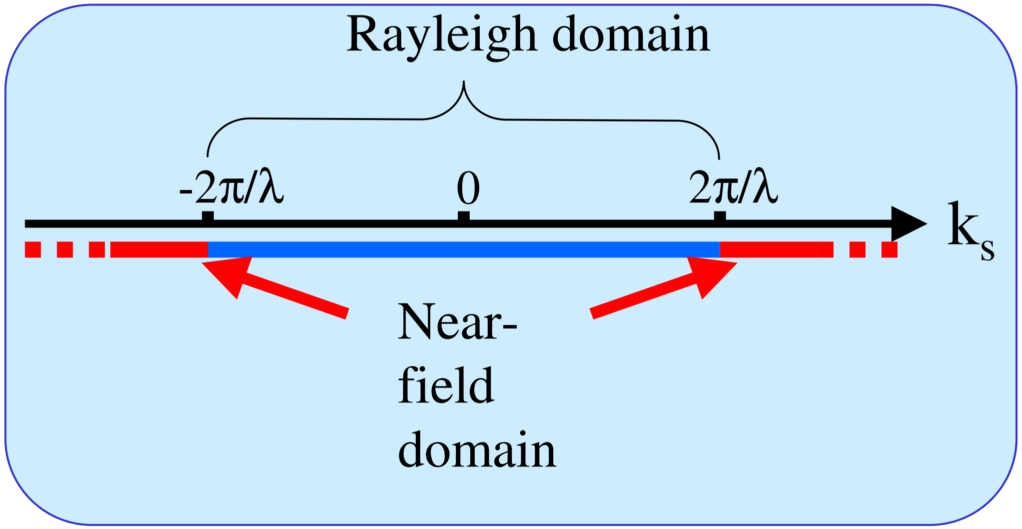
$\Delta s < \lambda/2 \Rightarrow \Delta k_s > 4\pi/\lambda$

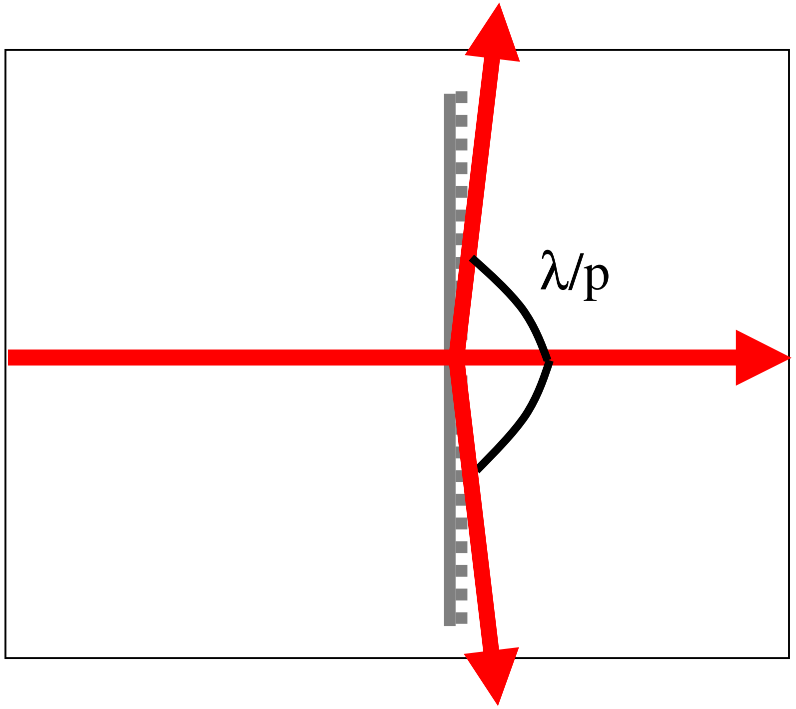
$k^2 = k_x^2 + k_y^2 + k_z^2 = (2\pi/\lambda)^2$

$k_x^2 + k_y^2 > (2\pi/\lambda)^2$

$\Rightarrow k_z^2 < 0$

$\mathbf{E} = \mathbf{E_0} \exp(-K_z\, z) \exp(j(\omega t - k_x x - k_y y))$
$k_z = jK_z$
evanescent waves





Δs: uncertainty on measure of P position

Δk_s: uncertainty on measure of wave vector

Heisenberg relation:

$$\Delta s . \Delta k_s \geq 2\pi$$

Rayleigh criterion: $\Delta s = \lambda/2$

$\Delta s < \lambda/2 \Rightarrow \Delta k_s > 4\pi/\lambda$

$k^2 = k_x^2 + k_y^2 + k_z^2 = (2\pi/\lambda)^2$

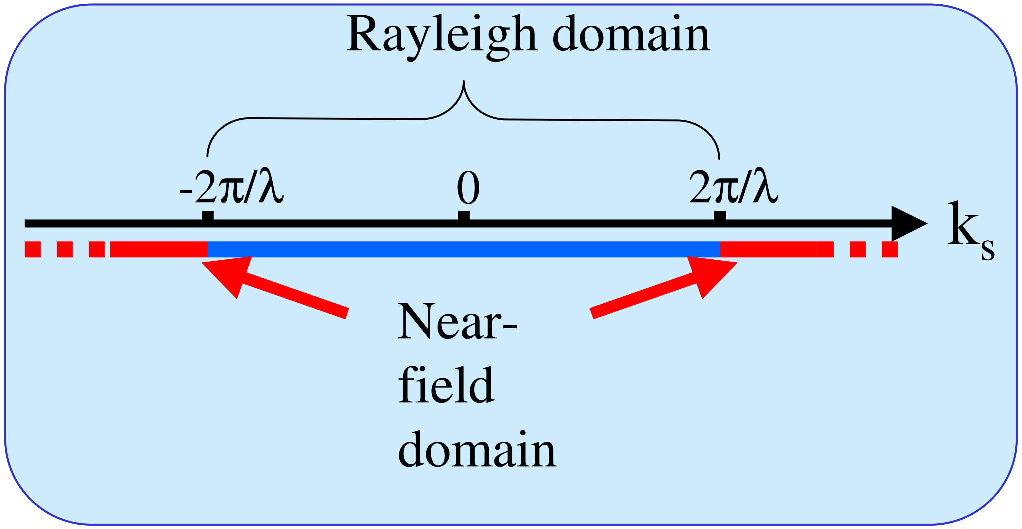
$k_x^2 + k_y^2 > (2\pi/\lambda)^2$

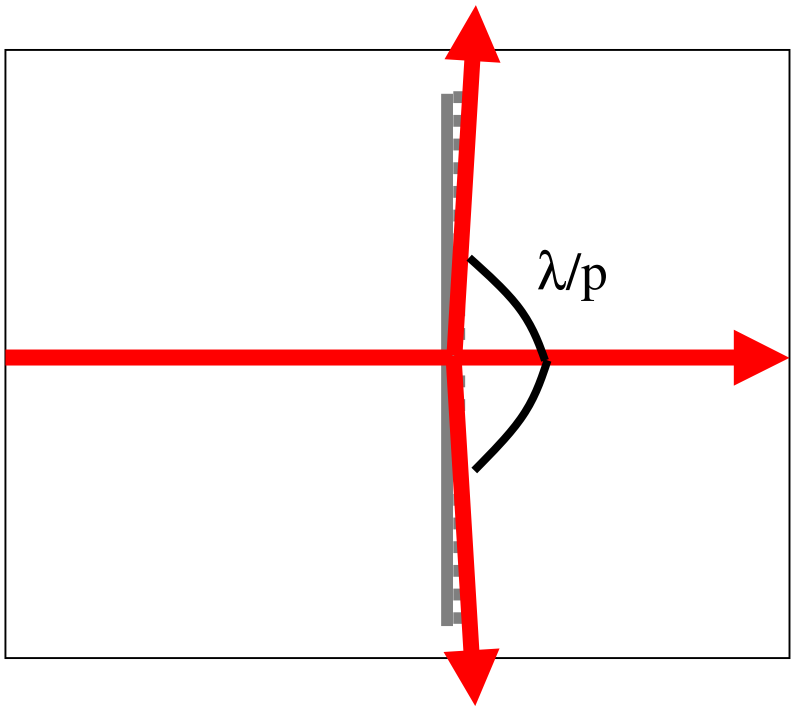
$\Rightarrow k_z^2 < 0$

$\mathbf{E} = \mathbf{E_0} \exp(-K_z\, z) \exp(j(\omega t - k_x x - k_y y))$

$k_z = jK_z$

evanescent waves





Δs: uncertainty on measure of P position

Δk$_s$: uncertainty on measure of wave vector

Heisenberg relation:

$$\Delta s . \Delta k_s \geq 2\pi$$

Rayleigh criterion: $\Delta s = \lambda/2$

$\Delta s < \lambda/2 \Rightarrow \Delta k_s > 4\pi/\lambda$

$k^2 = k_x^2 + k_y^2 + k_z^2 = (2\pi/\lambda)^2$

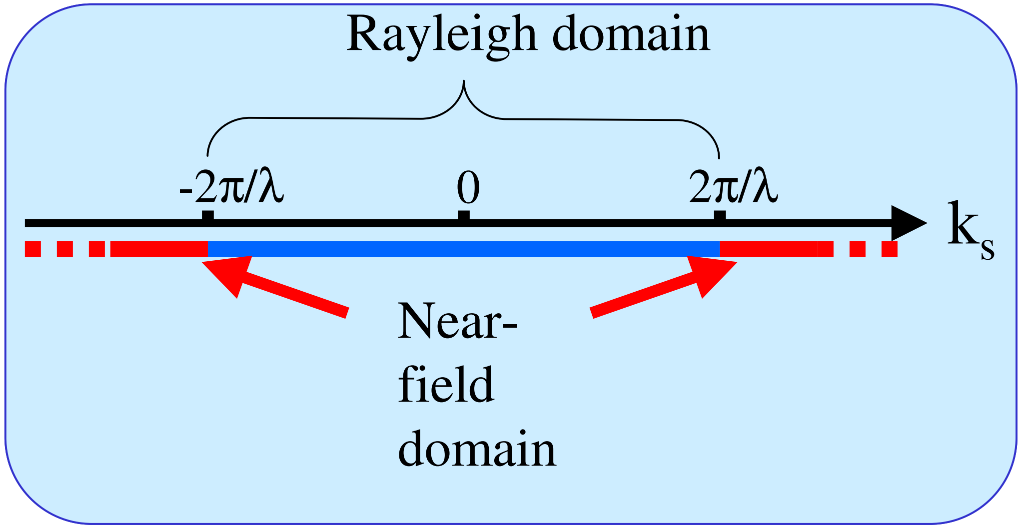
$k_x^2 + k_y^2 > (2\pi/\lambda)^2$

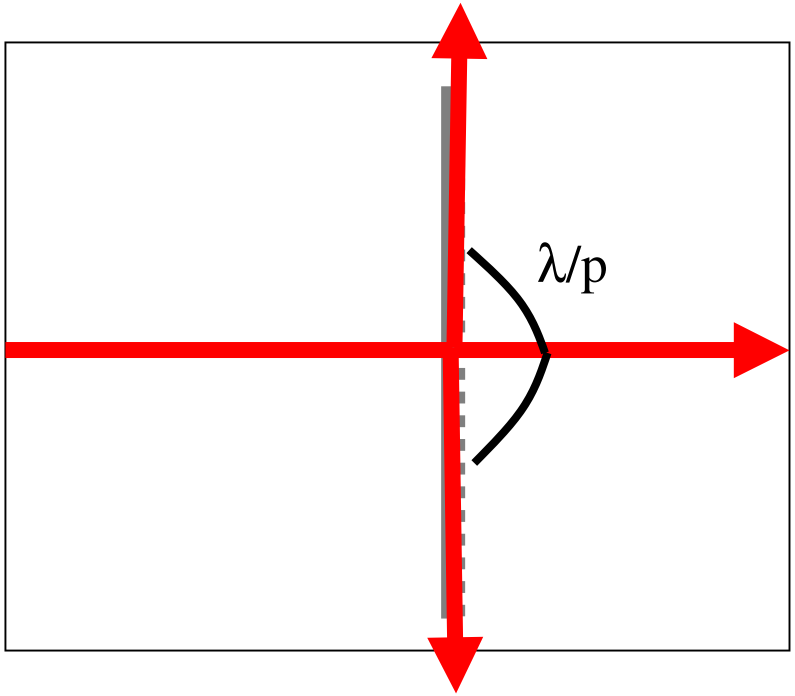
$\Rightarrow k_z^2 < 0$

$\mathbf{E} = \mathbf{E_0} \exp(-K_z z) \exp(j(\omega t - k_x x - k_y y))$

$k_z = jK_z$

evanescent waves





Δs: uncertainty on measure of P position

$\mathbf{\Delta k_s}$: uncertainty on measure of wave vector

Heisenberg relation:

$$\mathbf{\Delta s.\Delta k_s \geq 2\pi}$$

Rayleigh criterion: $\Delta s = \lambda/2$

$\Delta s < \lambda/2 \Rightarrow \Delta k_s > 4\pi/\lambda$

$k^2 = k_x^2 + k_y^2 + k_z^2 = (2\pi/\lambda)^2$

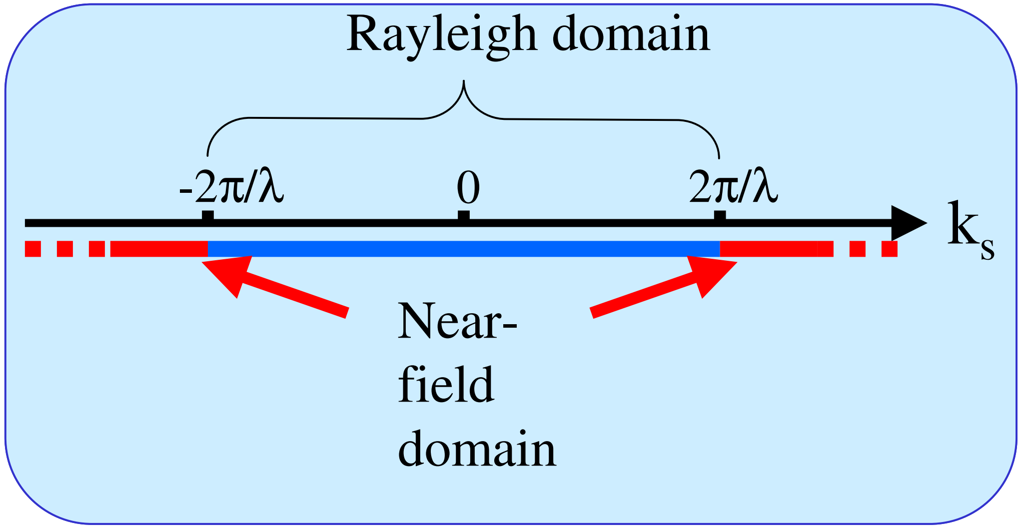
$k_x^2 + k_y^2 \mathbf{>} (2\pi/\lambda)^2$

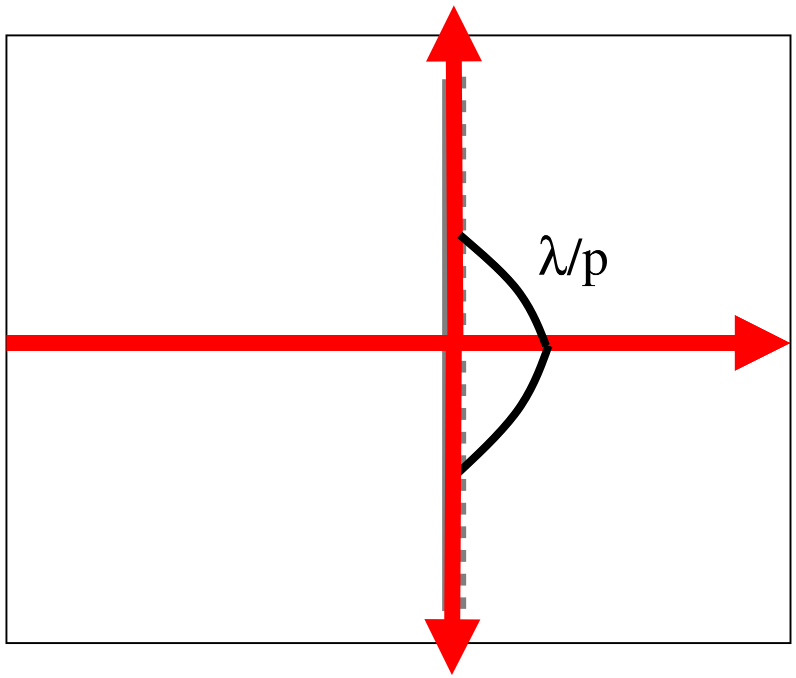
$\Rightarrow k_z^2 < 0$

$\mathbf{E} = \mathbf{E_0} \exp(-K_z z) \exp(j(\omega t - k_x x - k_y y))$

$k_z = jK_z$

evanescent waves





Δs: uncertainty on measure of P position

Δk_s: uncertainty on measure of wave vector

Heisenberg relation:

$$\mathbf{\Delta s.\Delta k_s \geq 2\pi}$$

Rayleigh criterion: $\Delta s = \lambda/2$

$\Delta s < \lambda/2 \Rightarrow \Delta k_s > 4\pi/\lambda$

$k^2 = k_x^2 + k_y^2 + k_z^2 = (2\pi/\lambda)^2$

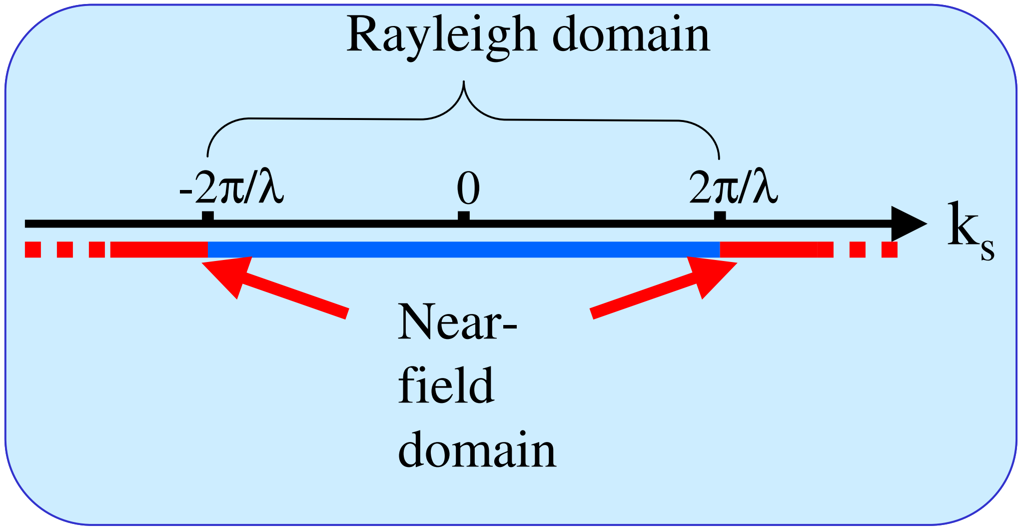
$k_x^2 + k_y^2 > (2\pi/\lambda)^2$

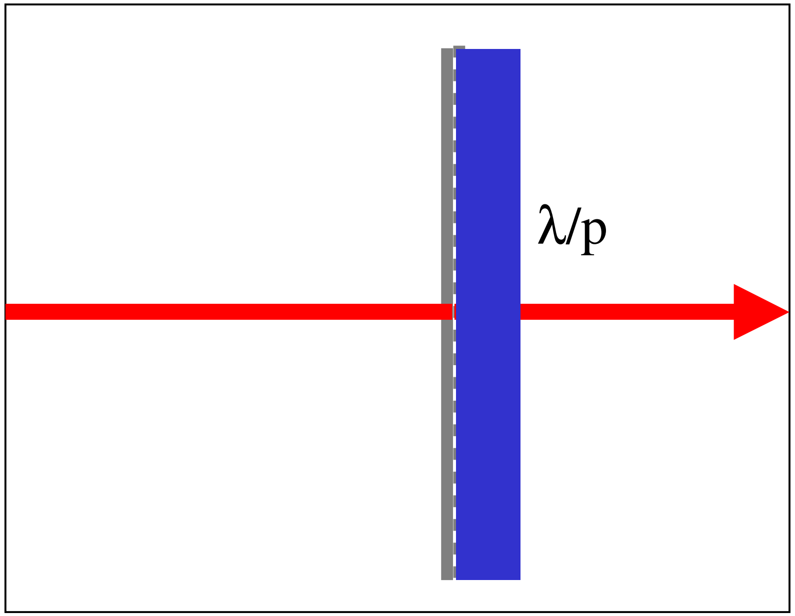
$\Rightarrow k_z^2 < 0$

$\mathbf{E} = \mathbf{E_0} \exp(-K_z z) \exp(j(\omega t - k_x x - k_y y))$

$k_z = jK_z$

evanescent waves





Δs: uncertainty on measure of P position

Δk_s: uncertainty on measure of wave vector

Heisenberg relation:

$$\Delta s . \Delta k_s \geq 2\pi$$

Rayleigh criterion: $\Delta s = \lambda/2$

$\Delta s < \lambda/2 \Rightarrow \Delta k_s > 4\pi/\lambda$

$k^2 = k_x^2 + k_y^2 + k_z^2 = (2\pi/\lambda)^2$

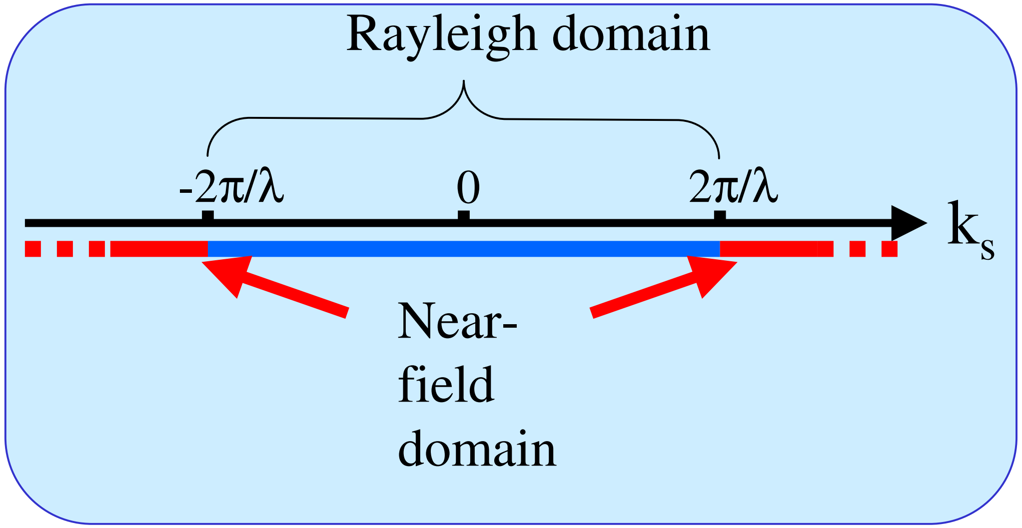
$k_x^2 + k_y^2 > (2\pi/\lambda)^2$

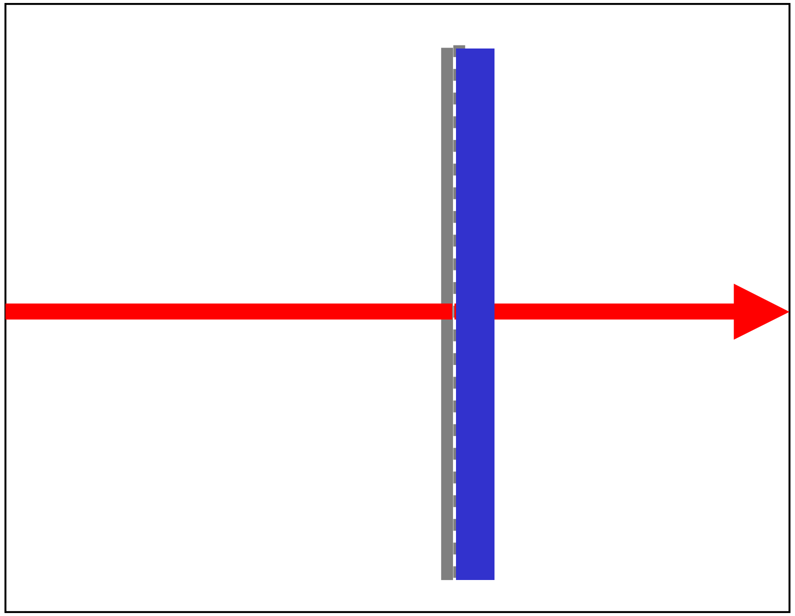
$\Rightarrow k_z^2 < 0$

$\mathbf{E} = \mathbf{E_0} \exp(-K_z z) \exp(j(\omega t - k_x x - k_y y))$

$k_z = jK_z$

evanescent waves





Δs: uncertainty on measure of P position

Δk_s: uncertainty on measure of wave vector

Heisenberg relation:

$$\Delta s . \Delta k_s \geq 2\pi$$

Rayleigh criterion: $\Delta s = \lambda/2$

$\Delta s < \lambda/2 \Rightarrow \Delta k_s > 4\pi/\lambda$

$k^2 = k_x^2 + k_y^2 + k_z^2 = (2\pi/\lambda)^2$

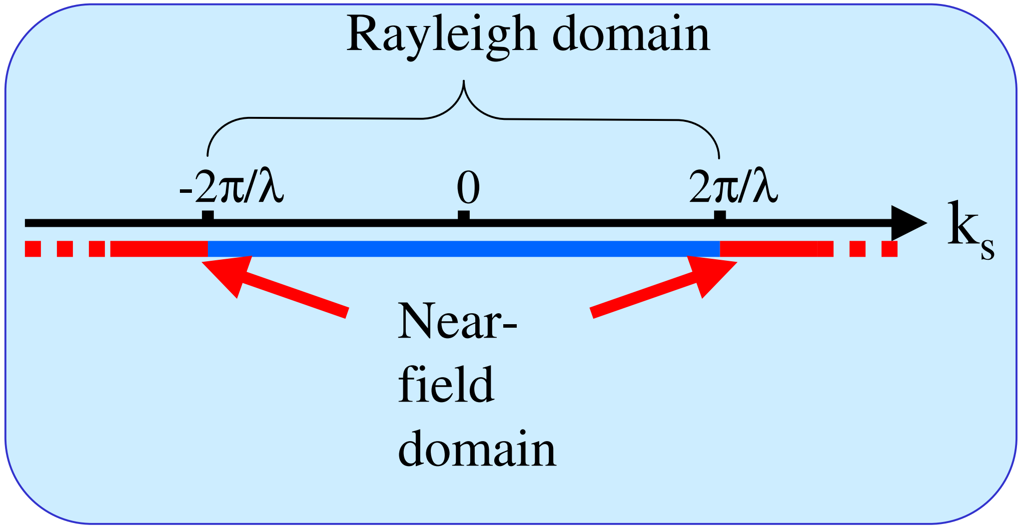
$k_x^2 + k_y^2 > (2\pi/\lambda)^2$

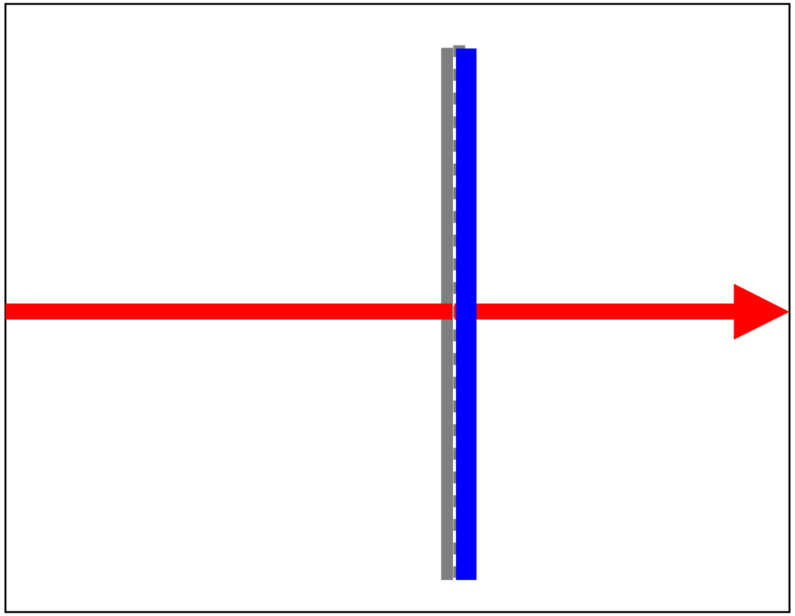
$\Rightarrow k_z^2 < 0$

$\mathbf{E} = \mathbf{E_0} \exp(-K_z z) \exp(j(\omega t - k_x x - k_y y))$

$k_z = jK_z$

evanescent waves





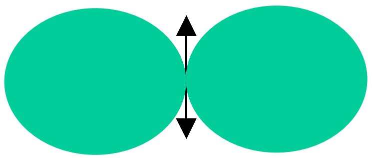
Some properties of the optical near-field

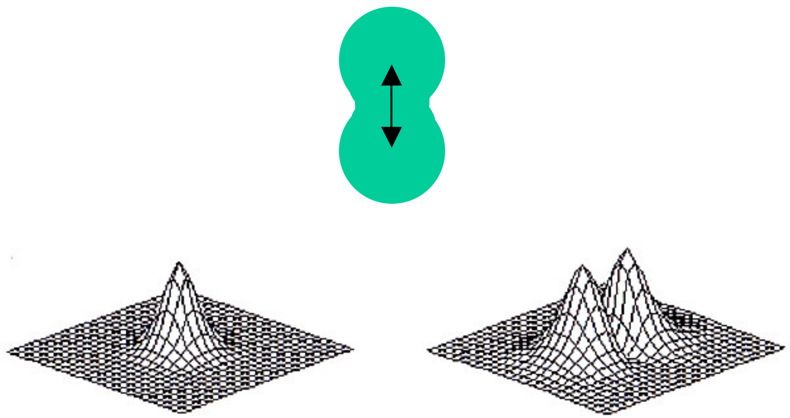
* Distance probe-sample plays the role of a low-pass filter

$$[E \propto E_0(t)\, \exp(-z/l_p)]$$

* The characteristic decay length: * is independent of the wavelength
  * depends on the period (Fourier component)
  * depends on the diffraction order number

* The emission diagram of the local oscillating dipoles is quite different in the far- and in the near-field





⊥ ||

* Resolution depends mainly on the lateral size of the probe

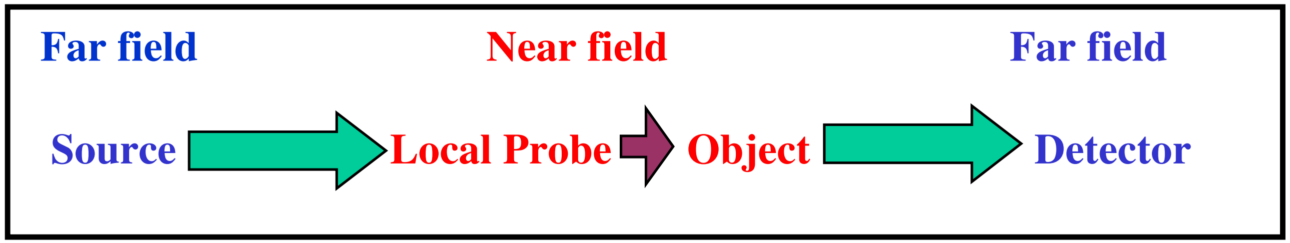
How to detect evanescent ligth?

The aim of the near-field microscopy is to provide images of the small details (having a characteristic length lower than $\lambda/2$) of objects.

These details diffract evanescent waves.

A local probe diffusing light towards the detection system or diffusing light in the near field is needed.

We have adopted the following scheme:



Outline

* Optical far-field, Rayleigh criterion and Near-field

* Some previous results

* Our experimental method

* Theoretical background

* The experimental set-up

* Some examples

Conclusions

Near-field magneto-optics and high density data storage
E. Betzig, J.K. Trautman, R. Wolfe, E.M. Gyorgy, P.L. Finn, M.H. Kryder, C.-H. Chang
Appl. Phys. Lett., 61 (1992) 142

A scanning near-field optical microscope for the imaging of magnetic domains in reflection

T. J. Silva[a] and S. Schultz
Center for Magnetic Recording Research, University of California, San Diego, 9500 Gilman Drive, La Jolla, California 92093-0401

Rev. Sci. Instrum. 67 (3), March 1996 0034-6748/96/67(3)/715/11/$10.00 **715**

Dichroic imaging of magnetic domains with a scanning near-field optical microscope

V. Kottler [a,b,1], N. Essaidi [a], N. Ronarch [a], C. Chappert [b], Y. Chen [a,*]

Journal of Magnetism and Magnetic Materials 165 (1997) 398–400

Versatile UHV system for combined far- and near-field magneto-optical microscopy of thin films

Gereon Meyer*, Tristan Crecelius, Günter Kaindl, Andreas Bauer
Institut für Experimentalphysik, Freie Universität Berlin, Fachbereich Physik, Arnimallee 14, D-14195 Berlin, Germany

J. Mag. Mag. Mat., 240 (2002) 76-78

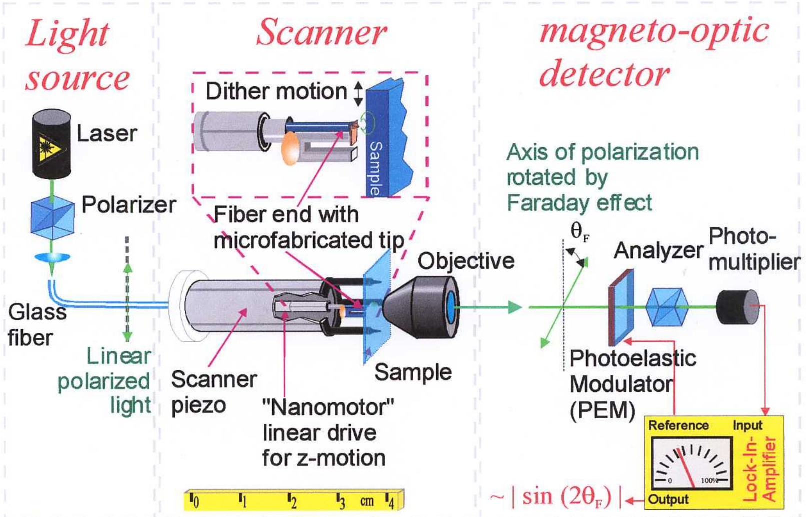
Observation of magnetic domains using a reflection-mode scanning near-field optical microscope

C. Durkan and I. V. Shvets[a)]
Department of Physics, Trinity College, Dublin 2, Ireland

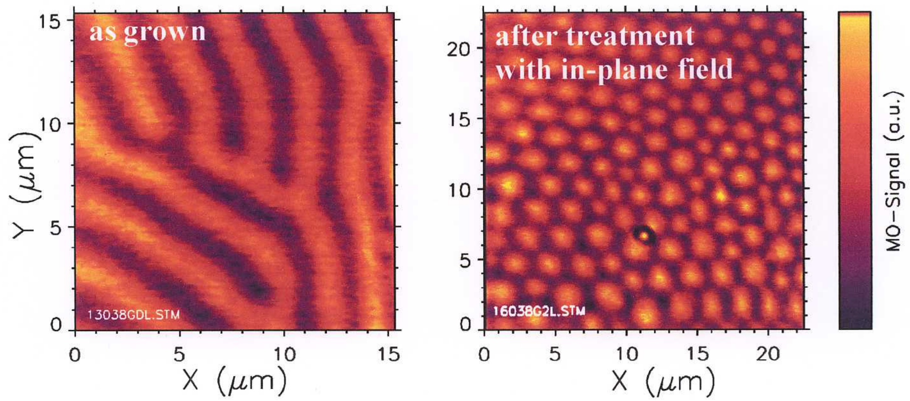
J. C. Lodder
MESA Research Institute, University of Twente, 7500 AE, Enschede, the Netherlands

Appl. Phys. Lett. **70** (10), 10 March 1997 0003-6951/97/70(10)/1323/3/$10.00 1323

Magneto-optic Scanning Near-field Microscopy in transmission mode



Transmission Mode Images of a Iron Garnet Film

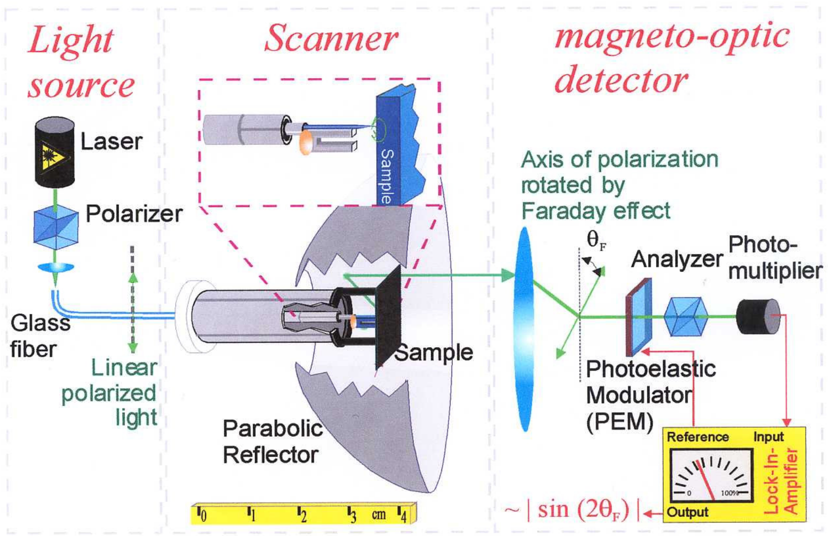


Courtesy of Dr. Eggers

RHEINISCH-WESTFÄLISCHE TECHNISCHE HOCHSCHULE AACHEN
II. Physikalisches Institut
Georg Eggers
Andreas Rosenberger
Prof. Dr. G. Güntherodt

Freie Universität Berlin
Institut für Experimentalphysik
Prof. Dr. Paul Fumagalli

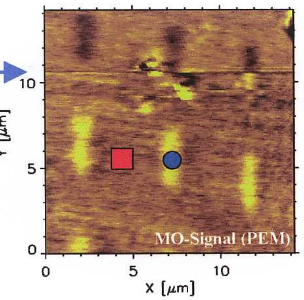
Magneto-optic Scanning Near-field Microscopy in reflection mode

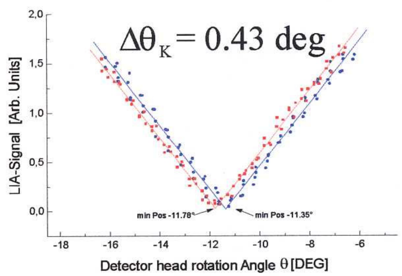


Reflection Mode Image of a Cobalt-Platinum Multilayer

with written domains as used for data storage

Turning the detector during the scan results in reversal of contrast





The local Kerr rotation angle can be measured by turning the detector head

RHEINISCH-WESTFÄLISCHE TECHNISCHE HOCHSCHULE AACHEN
RWTH
II. Physikalisches Institut
Georg Eggers
Andreas Rosenberger
Prof. Dr. G. Güntherodt

Freie Universität Berlin
Institut für Experimentalphysik
Prof. Dr. Paul Fumagalli

Courtesy of Dr. Eggers

Outline

* Optical far-field, Rayleigh criterion and Near-field

* Some previous results

* Our experimental method

* Theoretical background

* The experimental set-up

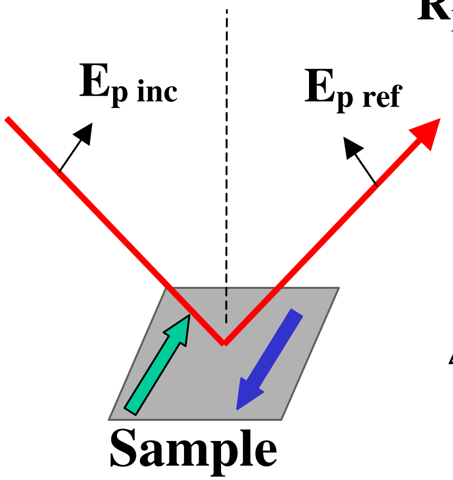
* Some examples

Conclusions

Transverse Kerr effect

- Far-field

$$R_p = R_{p0} \begin{cases} + \Delta R_p/2 \\ - \Delta R_p/2 \end{cases}$$



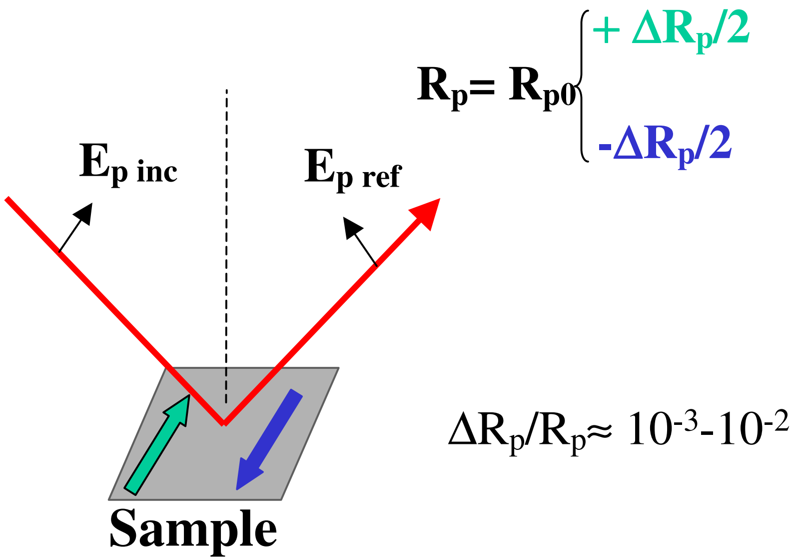
$\Delta R_p/R_p \approx 10^{-3}$-$10^{-2}$

Advantages (relative to the longitudinal Kerr):

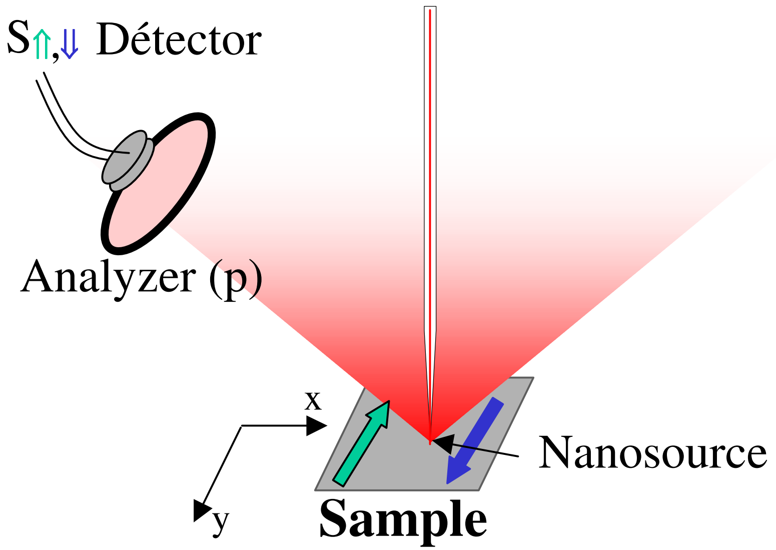
* maximum light (parallel polarizers)
* sensitivity to M_y only

Transverse Kerr effect

- **Far-field**



- **Near-field**



Advantages (relative to the longitudinal Kerr):

* maximum light (parallel polarizers)
* sensitivity to M_y only

Outline

* Optical far-field, Rayleigh criterion and Near-field

* Some previous results

* Our experimental method

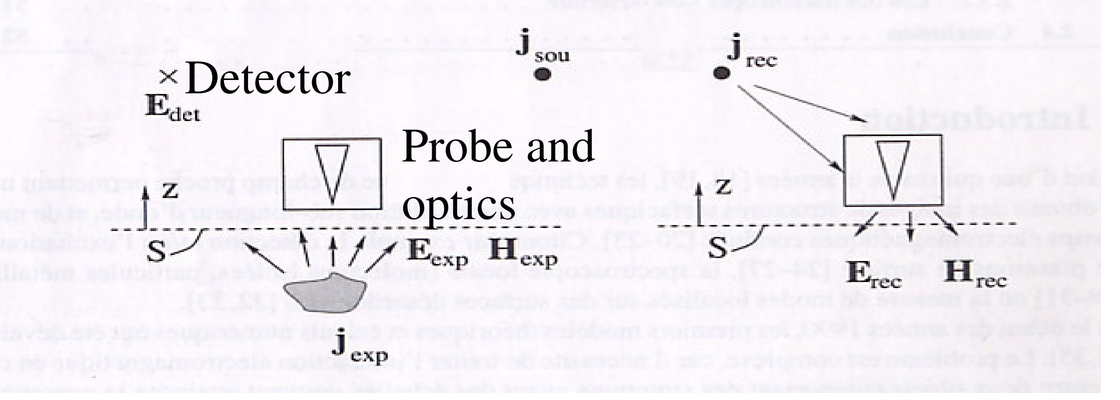
* Theoretical background

* The experimental set-up

* Some examples

Conclusions

Theorem of reciprocity applied to near-field optics



where $\mathbf{j}_{sou}$, $\mathbf{j}_{exp}$: current density in external source, in the sample

$\mathbf{E}_{exp}$, $\mathbf{H}_{exp}$: electric, magnetic fields radiated by the sample with the actual configuration

$\mathbf{E}_{det}$: electric field at the detector position

$\mathbf{j}_{rec}$: point source located at the detector position

$\mathbf{E}_{rec}$, $\mathbf{H}_{rec}$: reciprocal electric, magnetic fields without sample

$$\mathbf{E}_{rec}.\mathbf{j}_{rec}=\mathbf{E}_{rec}\,(\mathbf{r}_{sou}).\mathbf{j}_{sou}+\int_S(\mathbf{E}_{exp}\times\mathbf{H}_{rec}-\mathbf{E}_{rec}\times\mathbf{H}_{exp})\mathbf{e}_z dxdy$$

Component A of the electric field along the direction of the analyzer direction **p** at the detector position

$$A=\mathbf{E}_{exp\mathbf{p}}(\mathbf{r}_{det}).\mathbf{p} = 1/i\omega\int_V \mathbf{E}_{rec}.\mathbf{j}_{exp}d\mathbf{r}$$

Component A of the electric field along the direction of the analyzer direction **p** at the detector position

$$A = \mathbf{E}_{\exp\mathbf{p}}(\mathbf{r}_{det}).\mathbf{p} = 1/i\omega \int_V \mathbf{E}_{rec}.\mathbf{j}_{exp} d\mathbf{r}$$

$$\mathbf{j}_{exp} = \mathbf{j}_{\boldsymbol{\varepsilon}}$$

Component A of the electric field along the direction of the analyzer direction **p** at the detector position

$$A=\mathbf{E}_{\exp\mathbf{p}}(\mathbf{r}_{det}).\mathbf{p} = 1/i\omega \int_V \mathbf{E}_{rec}.\mathbf{j}_{\exp} d\mathbf{r}$$

Magnetization $M\hat{\mathbf{e}}$

$$\mathbf{j}_{\exp} = \mathbf{j}_{\varepsilon} + \mathbf{j}_{mag} = -i\omega\varepsilon_0[(\varepsilon_1-1)\mathbf{E}_{\exp}+ifM\hat{\mathbf{e}} \text{ X } \mathbf{E}_{\exp}]$$

Component A of the electric field along the direction of the analyzer direction **p** at the detector position

$$A=\mathbf{E}_{\exp}(\mathbf{r}_{det}).\mathbf{p} = 1/i\omega \int_V \mathbf{E}_{rec}.\mathbf{j}_{exp} d\mathbf{r}$$

Magnetization Mê

$$\mathbf{j}_{exp} = \mathbf{j}_{\varepsilon} + \mathbf{j}_{mag} = -i\omega\varepsilon_0[(\varepsilon_1-1)\mathbf{E}_{exp}+ifM\hat{\mathbf{e}} \times \mathbf{E}_{exp}]$$

$$A_{mag} = -if\varepsilon_0 \int_v M\hat{\mathbf{e}}.(\mathbf{E}_{exp} \times \mathbf{E}_{rec})d\mathbf{r}$$

$\mathbf{R}=(x,y)$; probe at height z_{tip}

$$A_{mag}(\mathbf{r}_{tip}) = \int_v H_{mag}(\mathbf{R}-\mathbf{R}_{tip}, z, z_{tip})\, M(\mathbf{r})d\mathbf{r}$$

Cst-height amplitude response for the magnetization in the sample plane z

$$H_{mag} \propto \hat{\mathbf{e}}.(\mathbf{E}_{exp} \times \mathbf{E}_{rec})$$

Component A of the electric field along the direction of the analyzer direction **p** at the detector position

$$A=\mathbf{E}_{exp}(\mathbf{r}_{det}).\mathbf{p} = 1/i\omega \int_V \mathbf{E}_{rec}.\mathbf{j}_{exp} d\mathbf{r}$$

Magnetization M**ê**

$$\mathbf{j}_{exp} = \mathbf{j}_\varepsilon + \mathbf{j}_{mag} = -i\omega\varepsilon_0[(\varepsilon_1-1)\mathbf{E}_{exp} + if M\hat{\mathbf{e}} \times \mathbf{E}_{exp}]$$

$$A_{mag} = -if\varepsilon_0 \int_v M\hat{\mathbf{e}}.(\mathbf{E}_{exp} \times \mathbf{E}_{rec})d\mathbf{r}$$

R=(x,y); probe at height z_{tip}

$$A_{mag}(\mathbf{r}_{tip}) = \int_v H_{mag}(\mathbf{R}-\mathbf{R}_{tip}, z, z_{tip})\, M(\mathbf{r})d\mathbf{r}$$

Cst-height amplitude response for the magnetization in the sample plane z

$$H_{mag} \propto \hat{\mathbf{e}}.(\mathbf{E}_{exp} \times \mathbf{E}_{rec})$$

$$A(M=0)(r_{tip}) = \int_v H_\varepsilon(R-R_{tip}, z, z_{tip})\varepsilon_1(r)d\mathbf{r}$$

Response function:

$$H_\varepsilon \propto \mathbf{E}_{exp}.\mathbf{E}_{rec}$$

Component A of the electric field along the direction of the analyzer direction **p** at the detector position

$$A = \mathbf{E}_{exp}(\mathbf{r}_{det}).\mathbf{p} = 1/i\omega \int_V \mathbf{E}_{rec}.\mathbf{J}_{exp} d\mathbf{r}$$

Magnetization Mê

$$\mathbf{j}_{exp} = \mathbf{j}_{\varepsilon} + \mathbf{j}_{mag} = -i\omega\varepsilon_0[(\varepsilon_1 - 1)\mathbf{E}_{exp} + if M\hat{\mathbf{e}} \times \mathbf{E}_{exp}]$$

$$A_{mag} = -if\varepsilon_0 \int_v M\hat{\mathbf{e}}.(\mathbf{E}_{exp} \times \mathbf{E}_{rec}) d\mathbf{r}$$

$\mathbf{R}=(x,y)$; probe at height z_{tip}

$$A_{mag}(\mathbf{r}_{tip}) = \int_v H_{mag}(\mathbf{R} - \mathbf{R}_{tip}, z, z_{tip}) M(\mathbf{r}) d\mathbf{r}$$

Cst-height amplitude response for the magnetization in the sample plane z

$$H_{mag} \propto \hat{\mathbf{e}}.(\mathbf{E}_{exp} \times \mathbf{E}_{rec})$$

$$A(M=0)(r_{tip}) = \int_v H_{\varepsilon}(R - R_{tip}, z, z_{tip}) \varepsilon_1(r) d\mathbf{r}$$

Response function:

$$H_{\varepsilon} \propto \mathbf{E}_{exp}.\mathbf{E}_{rec}$$

Reciprocal field: plane wave $\Rightarrow$

$$E_{rec} = k_2 \exp(ikr)/r.(-\cos\theta\ x + \sin\theta\ z)$$

Component A of the electric field along the direction of the analyzer direction **p** at the detector position

$$A=\mathbf{E}_{exp}(\mathbf{r}_{det}).\mathbf{p} = 1/i\omega \int_V \mathbf{E}_{rec}.\mathbf{J}_{exp} d\mathbf{r}$$

Magnetization $M\hat{\mathbf{e}}$

$$\mathbf{j}_{exp} = \mathbf{j}_{\varepsilon} + \mathbf{j}_{mag} = -i\omega\varepsilon_0[(\varepsilon_1-1)\mathbf{E}_{exp}+ifM\hat{\mathbf{e}} \times \mathbf{E}_{exp}]$$

$$A_{mag}=-if\varepsilon_0 \int_v M\hat{\mathbf{e}}.(\mathbf{E}_{exp} \times \mathbf{E}_{rec})d\mathbf{r}$$

$\mathbf{R}=(x,y)$; probe at height z_{tip}

$$A_{mag}(\mathbf{r}_{tip})= \int_v H_{mag}(\mathbf{R}-\mathbf{R}_{tip}, z, z_{tip})\, M(\mathbf{r})d\mathbf{r}$$

Cst-height amplitude response for the magnetization in the sample plane z

$$H_{mag} \propto \hat{\mathbf{e}}.(\mathbf{E}_{exp} \times \mathbf{E}_{rec})$$

$$A(M=0)(r_{tip})= \int_v H_{\varepsilon}(R-R_{tip}, z, z_{tip})\varepsilon_1(r)d\mathbf{r}$$

Response function:

$$H_{\varepsilon} \propto \mathbf{E}_{exp}.\mathbf{E}_{rec}$$

Reciprocal field: plane wave $\Rightarrow$

$$E_{rec}=k_2 \exp(ikr)/r.(-\cos\theta\ x + \sin\theta\ z)$$

Response functions: $H_{mag} \propto \mathbf{y}.(\mathbf{E}_{exp} \wedge (-\cos\theta\ \mathbf{x} + \sin\theta\ \mathbf{z}))= \mathbf{E}_{exp}\ (\cos\theta\ \mathbf{z} + \sin\theta\ \mathbf{x})$

$H_{\varepsilon} \propto \mathbf{E}_{exp}.(-\cos\theta\ \mathbf{x} + \sin\theta\ \mathbf{z})$

Outline

* Optical far-field, Rayleigh criterion and Near-field

* Some previous results

* Our experimental method

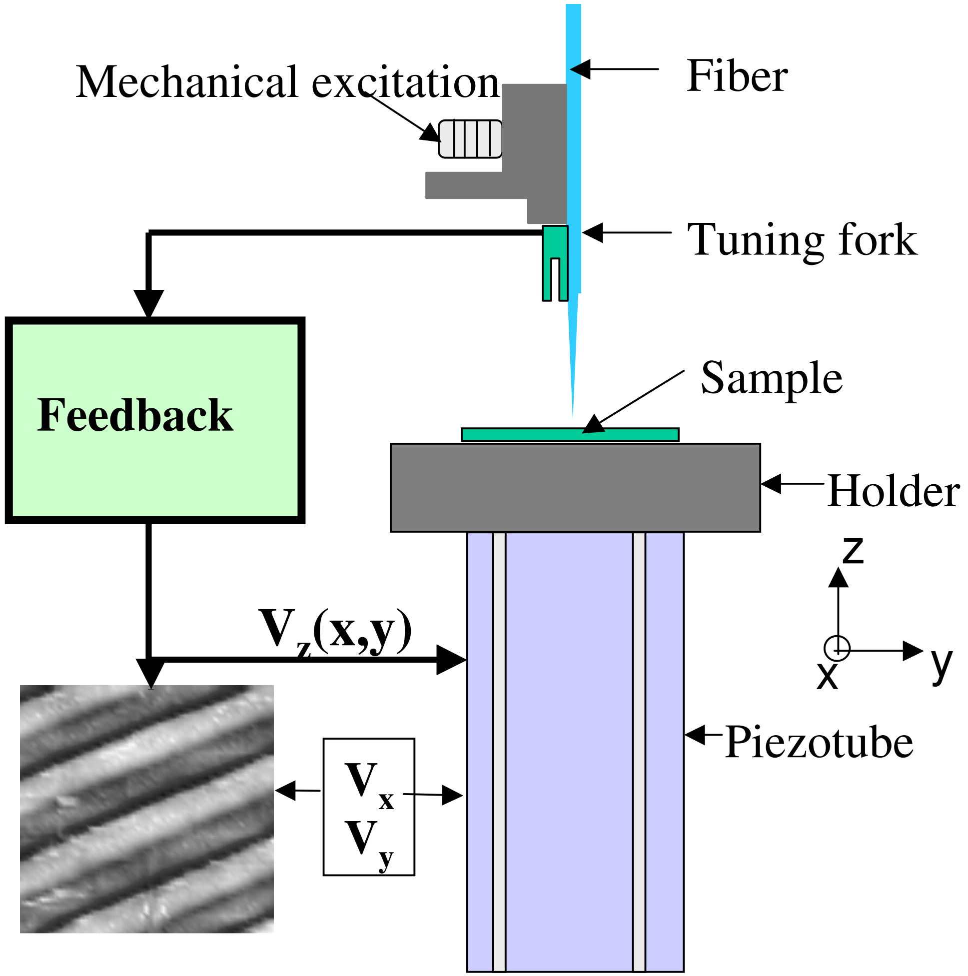
* Theoretical background

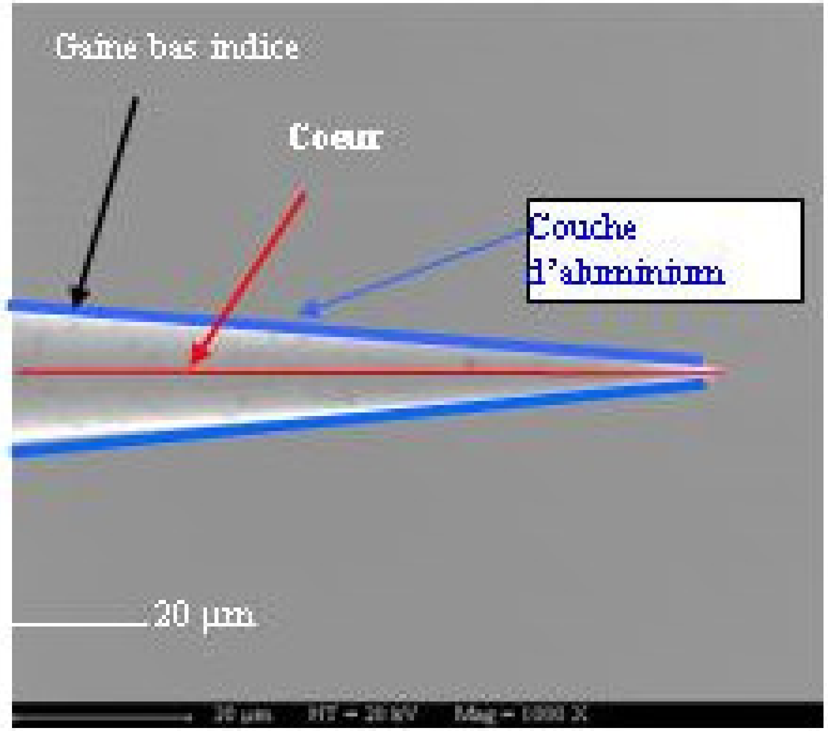
* The experimental set-up

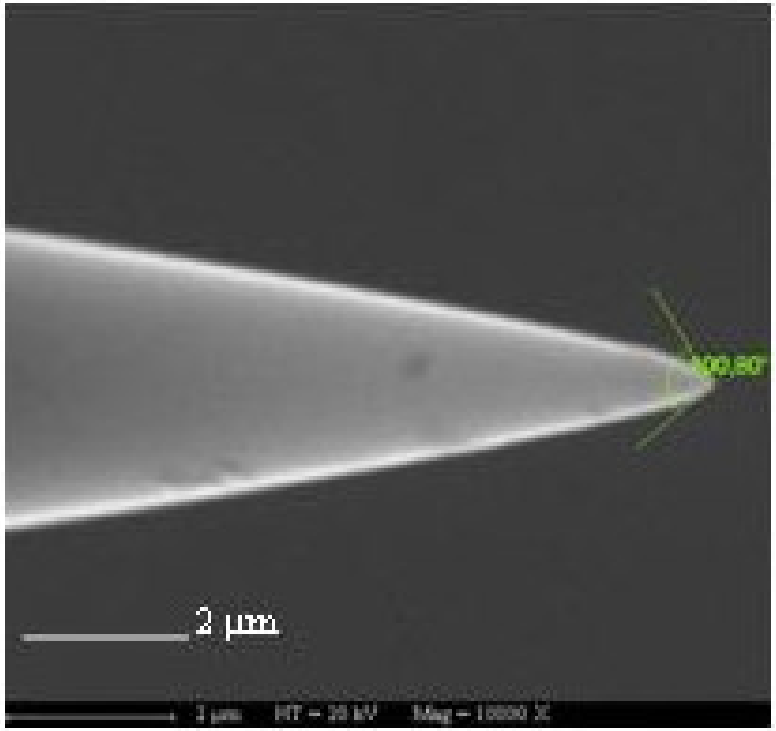
* Some examples

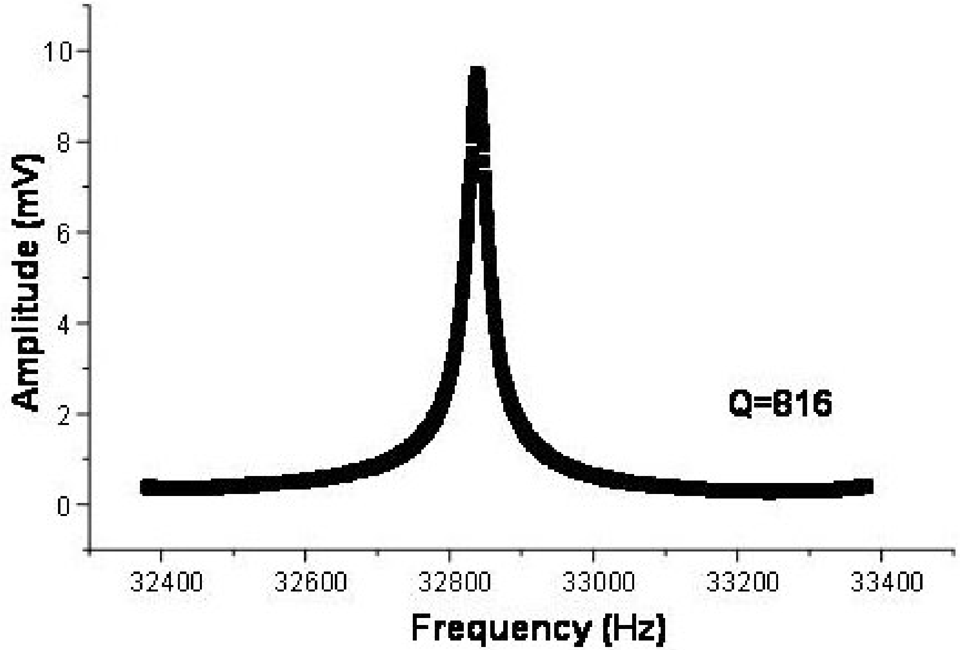
Conclusions

The topographic imaging

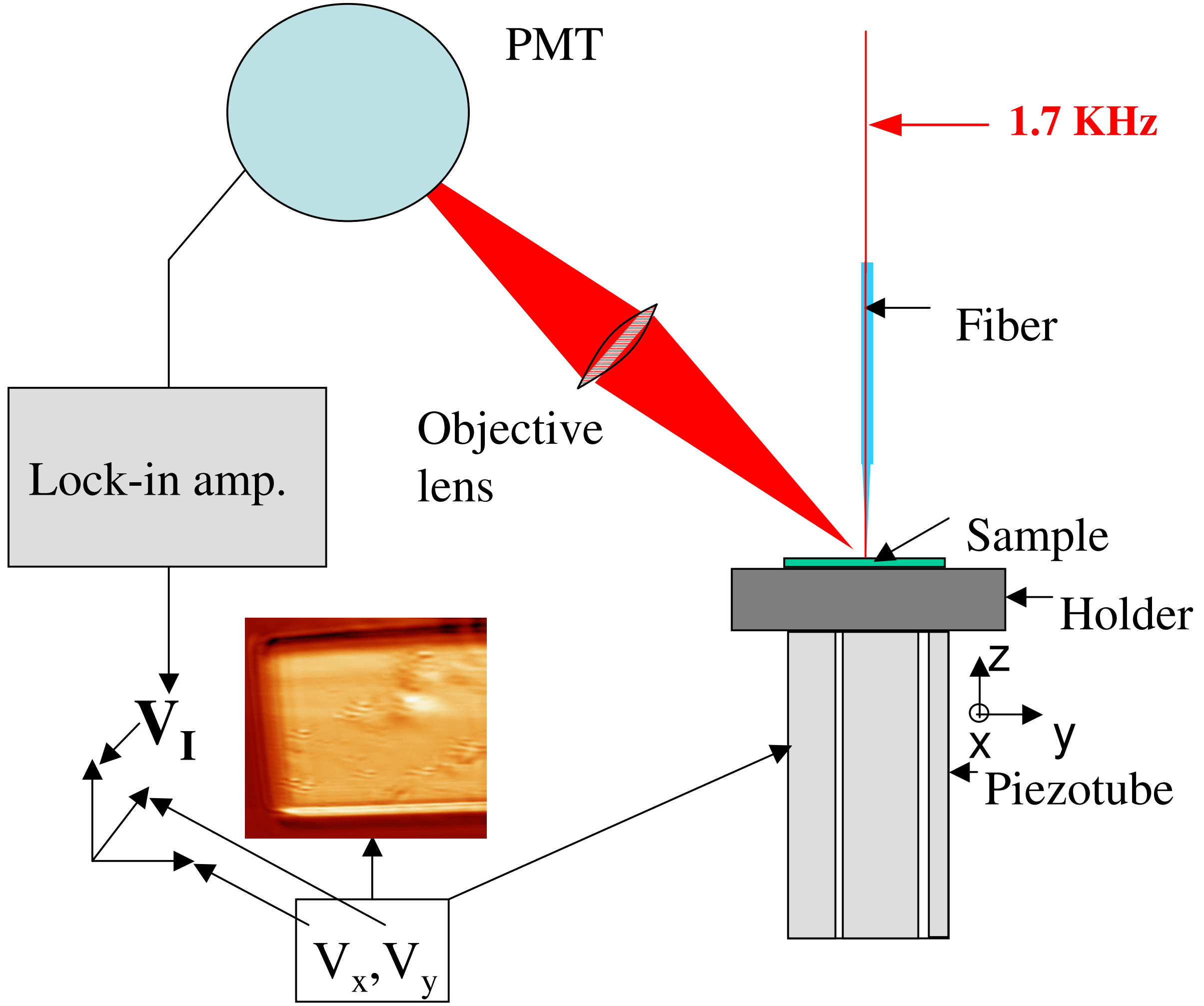



Gaine bas indice
Coeur
Couche
d'aluminium
20 µm

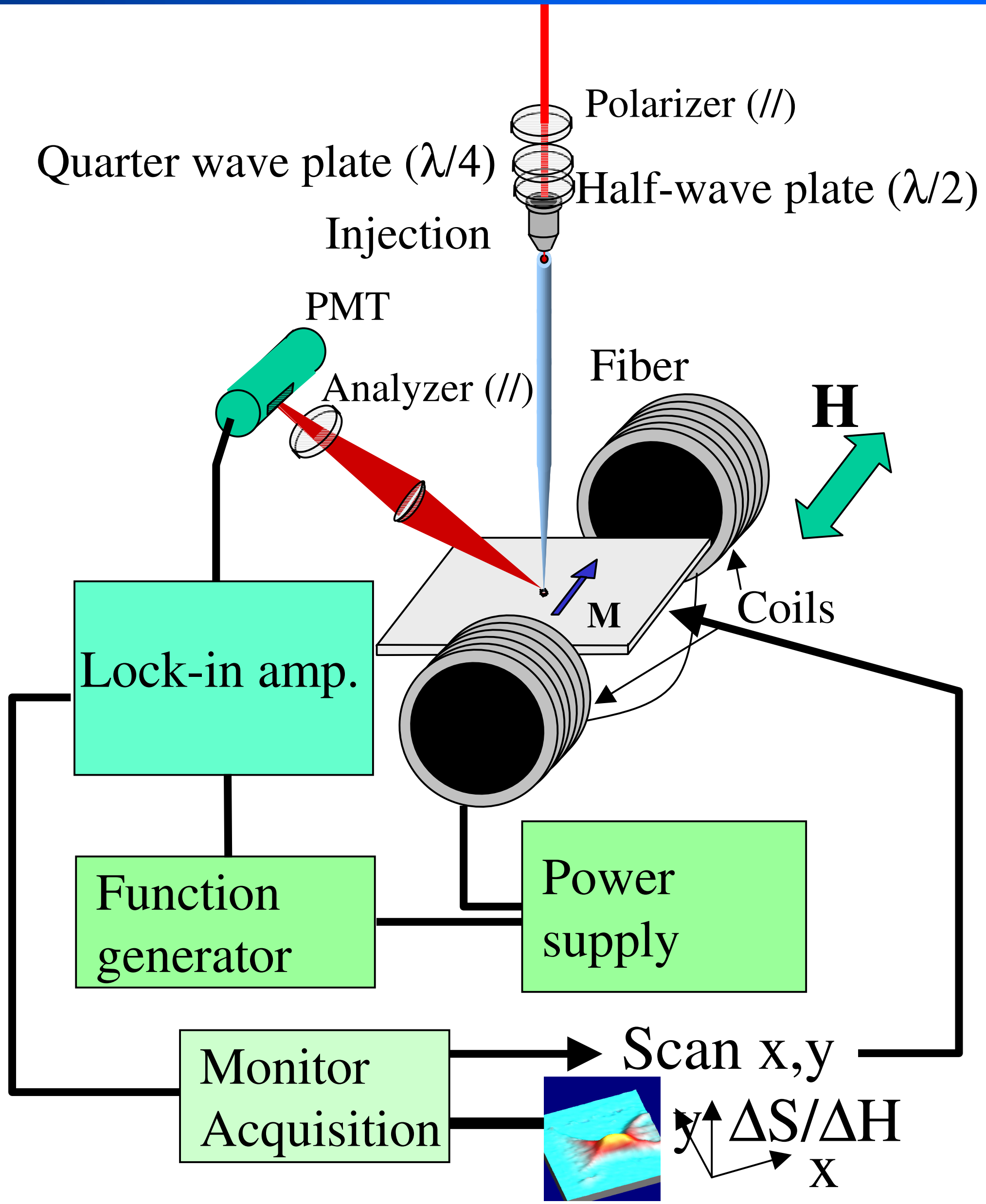

2 µm

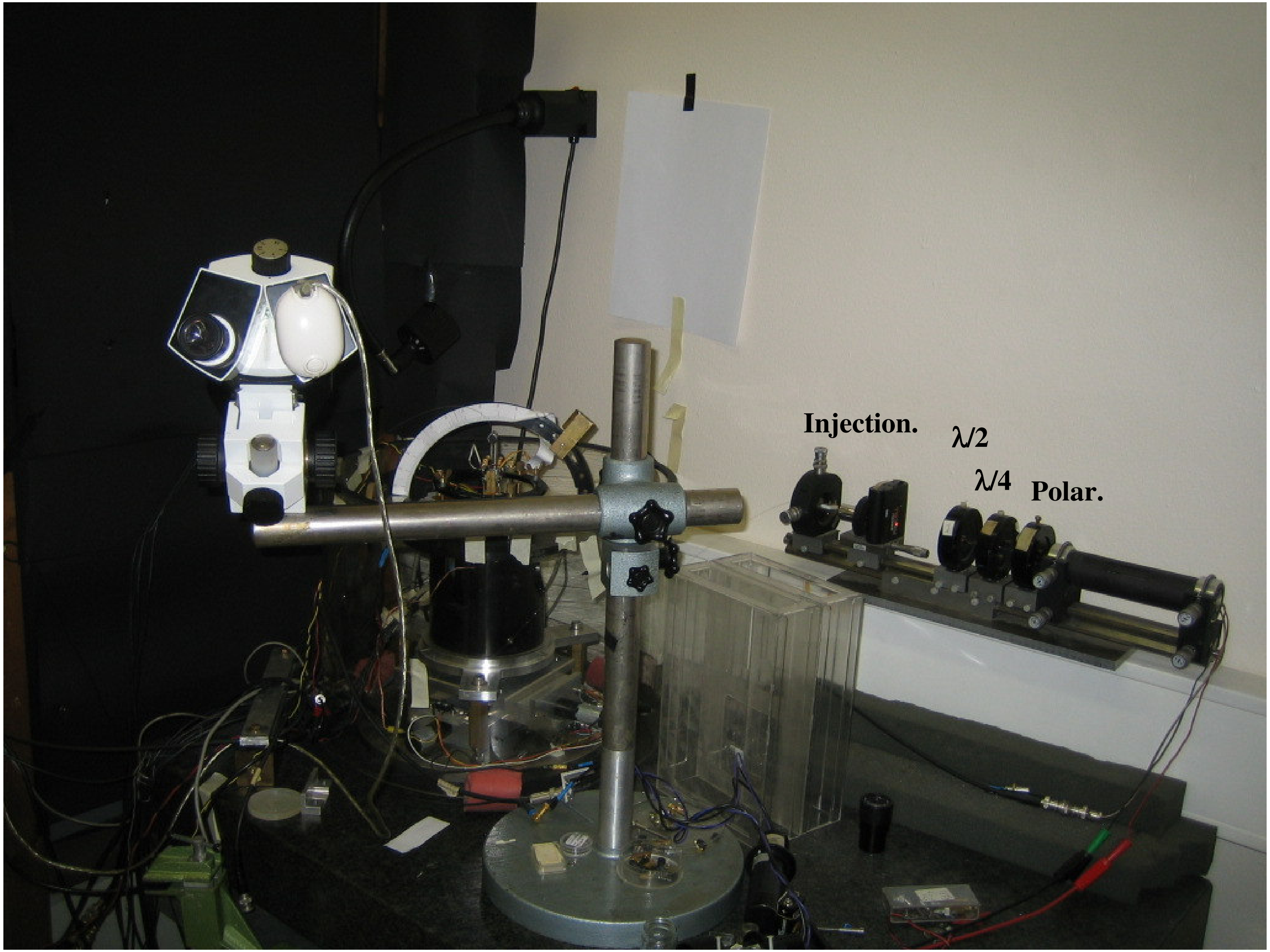

Amplitude (mV)
10
8
6
4
2
0
32400
32600
32800
33000
33200
33400
Frequency (Hz)
Q=816

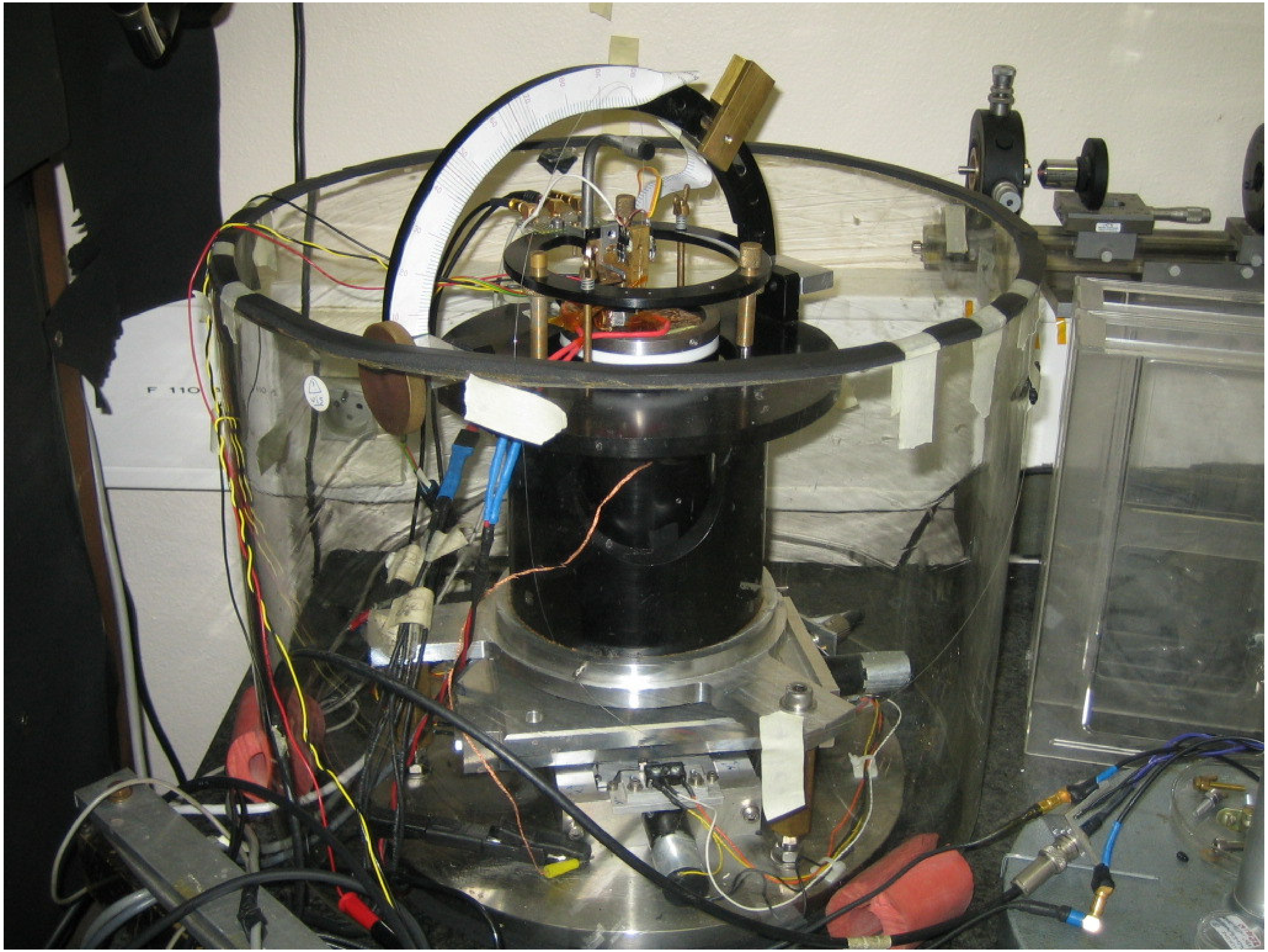
The optical imaging

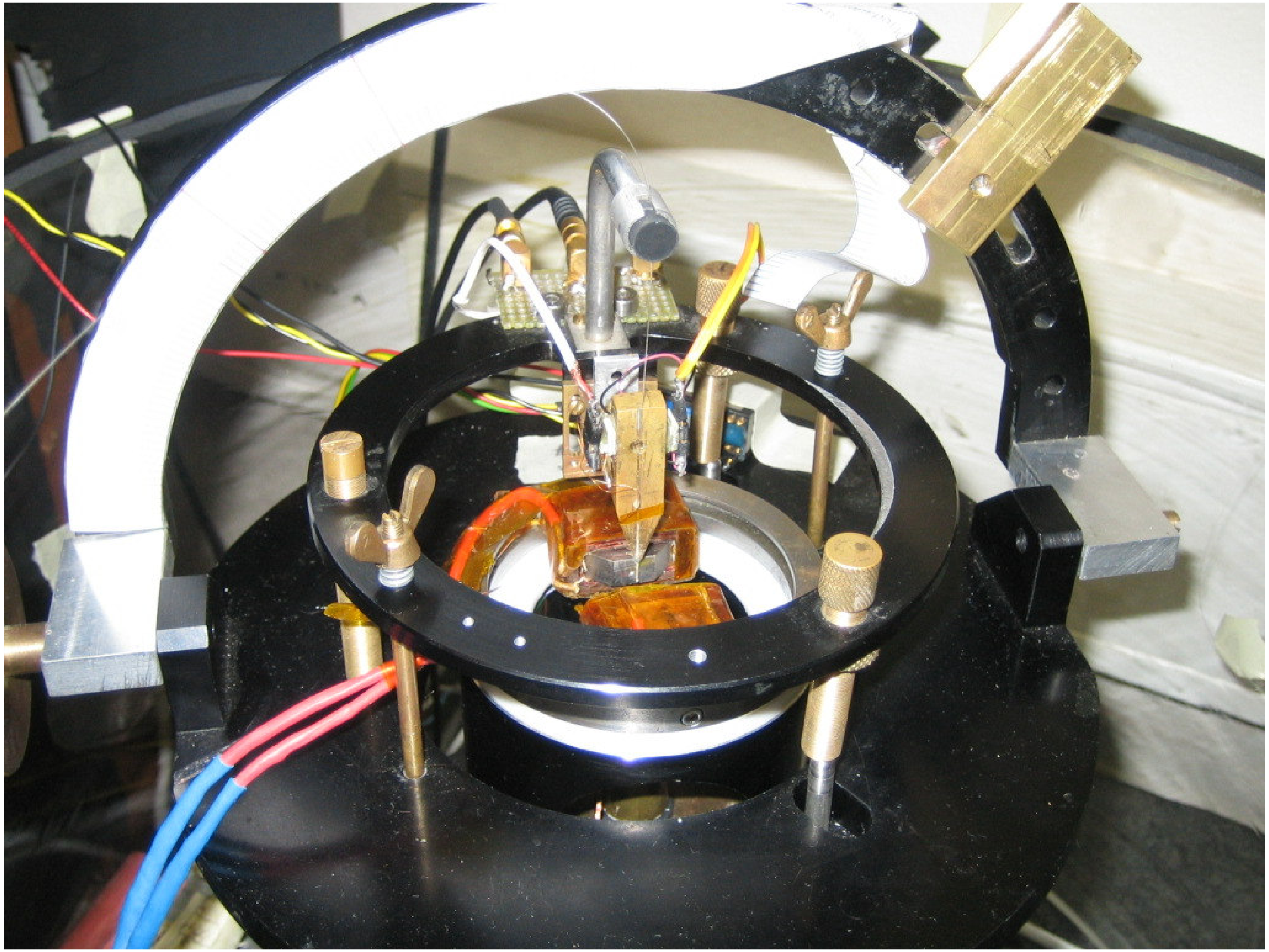


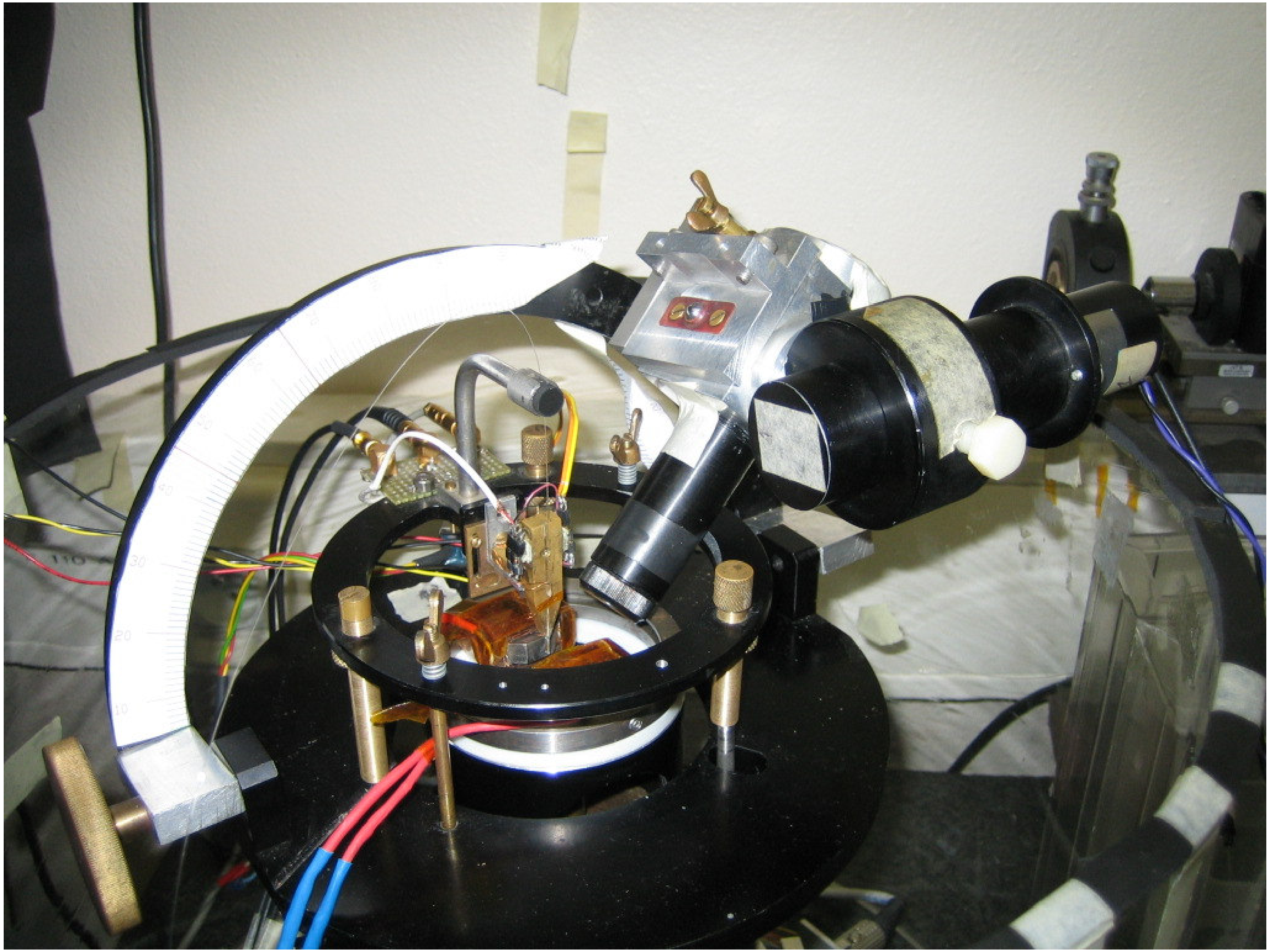
The magneto-optical imaging

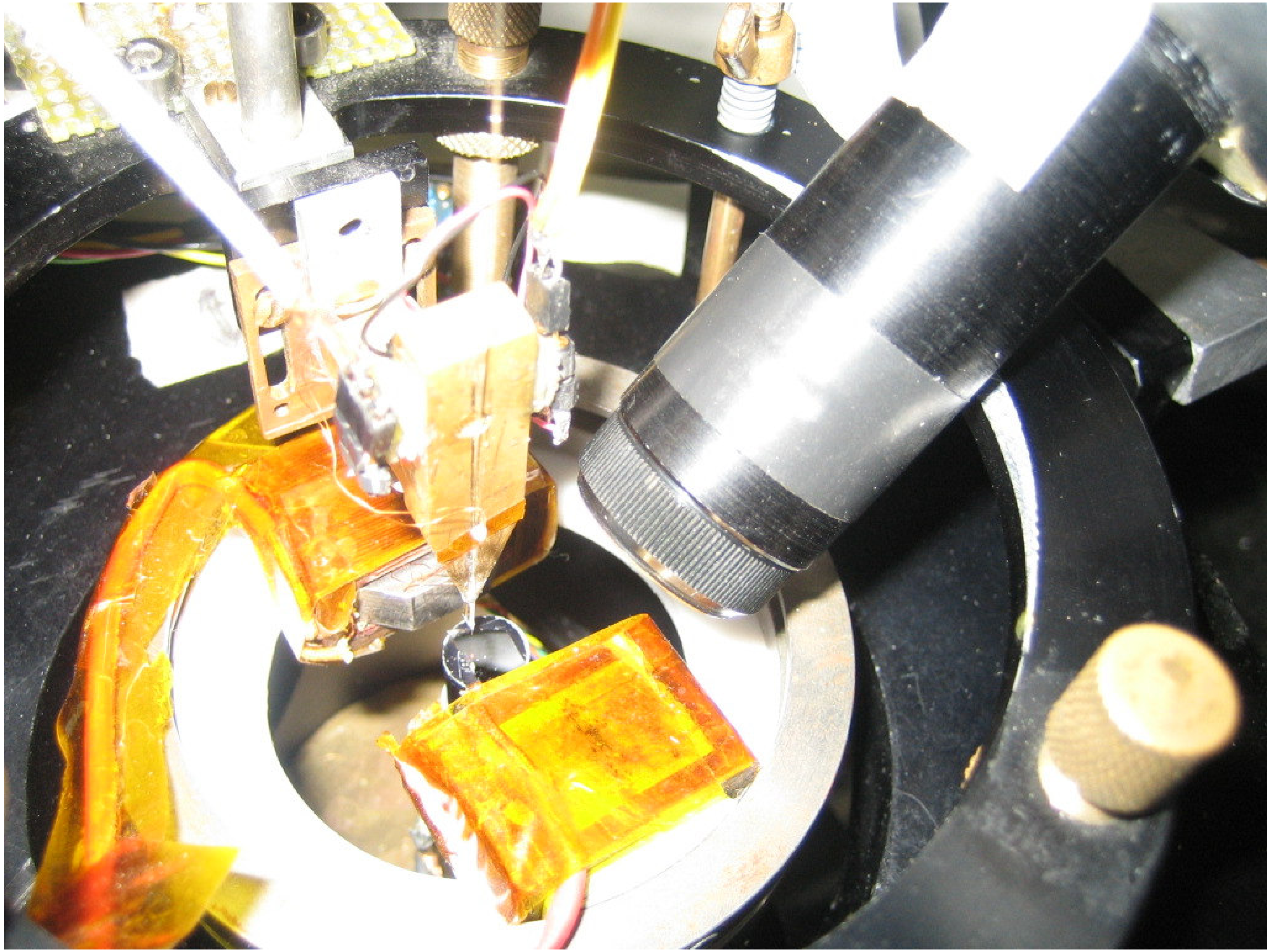


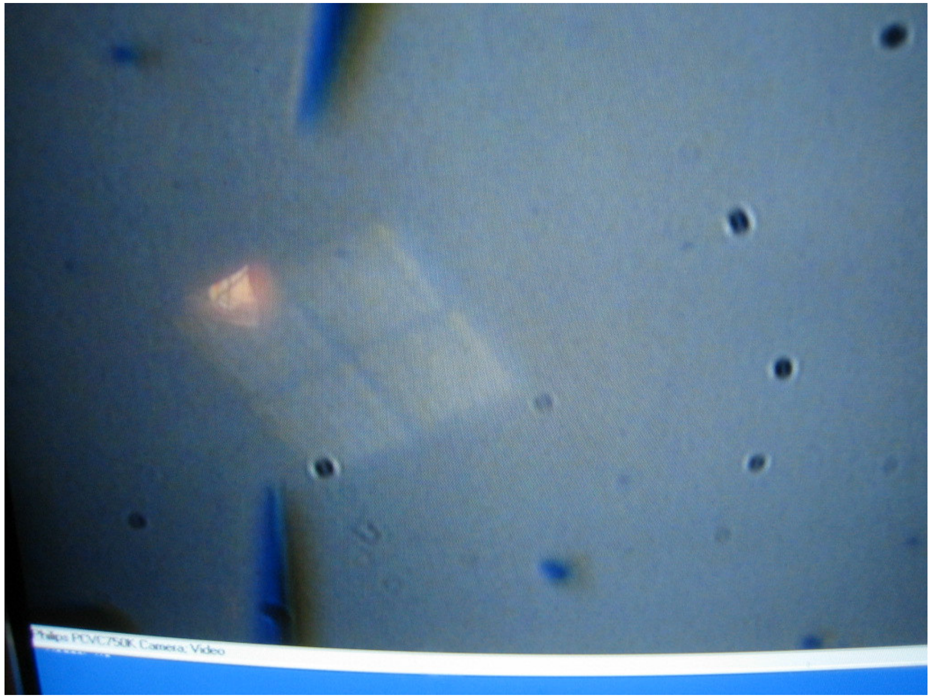

Injection.
λ/2
λ/4
Polar.

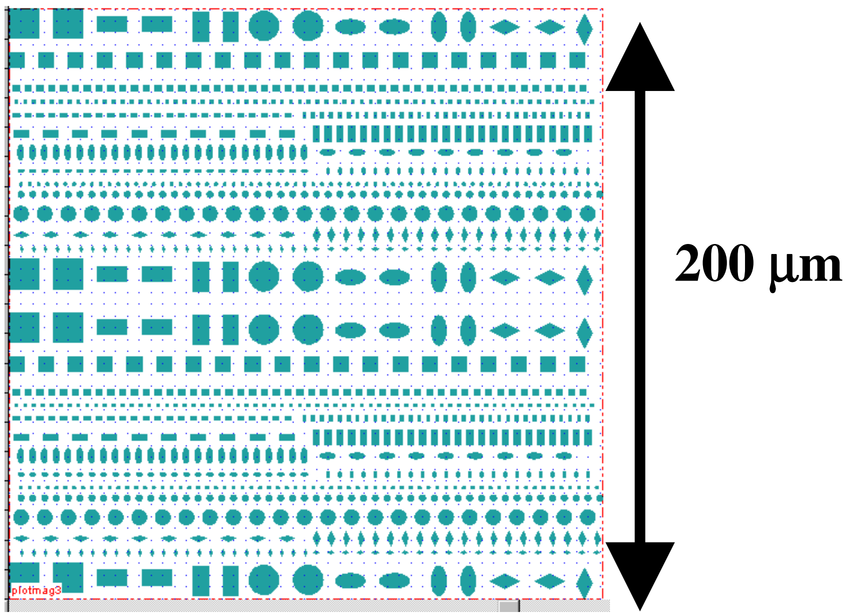

F 110

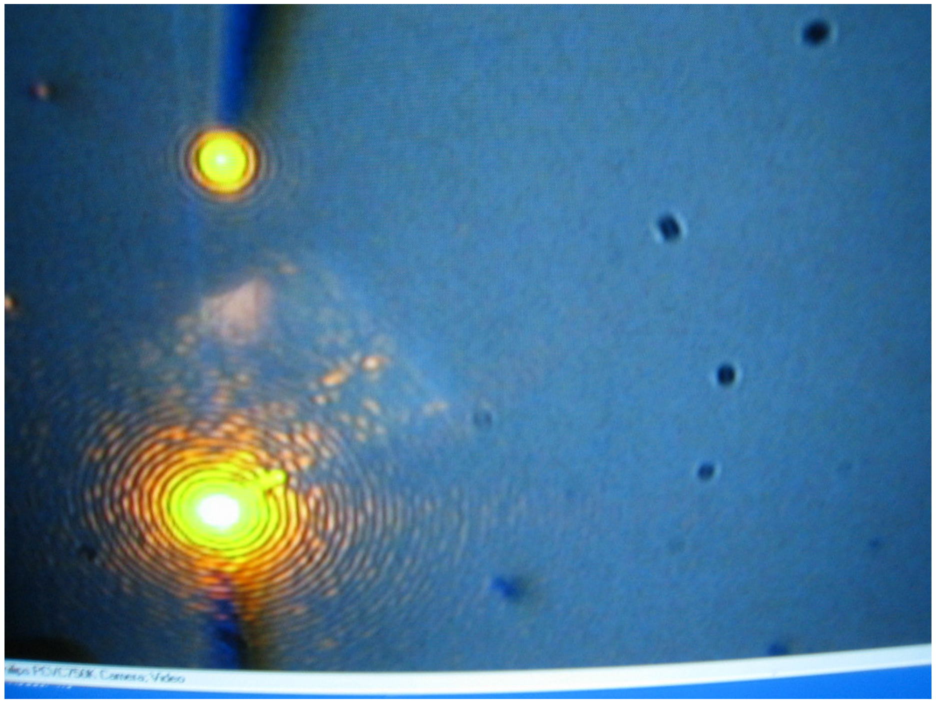









200 µm



Outline

* Optical far-field, Rayleigh criterion and Near-field

* Some previous results

* Our experimental method

* Theoretical background

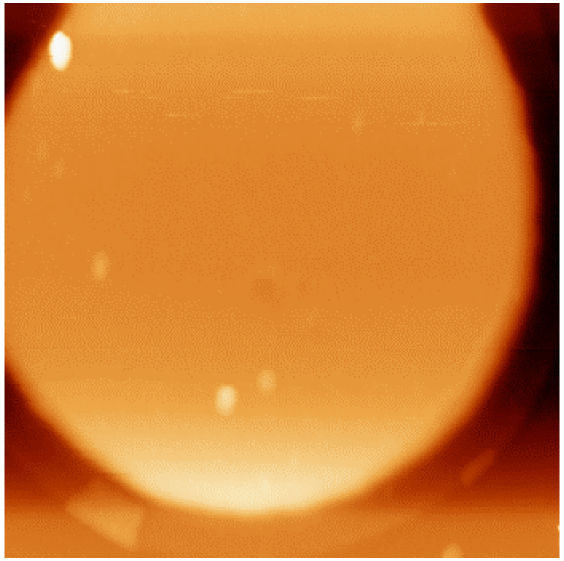
* The experimental set-up

* Some examples

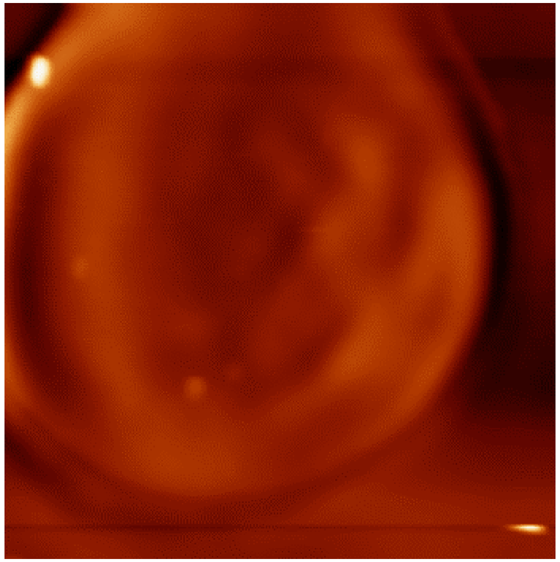
Conclusions

Thin film disk
Ø 5 µm; 50 nm thick
FeCoSiB

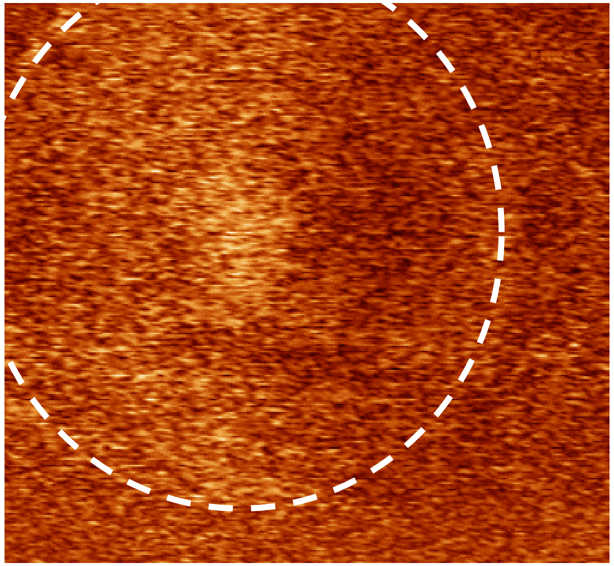
Topography



Optics



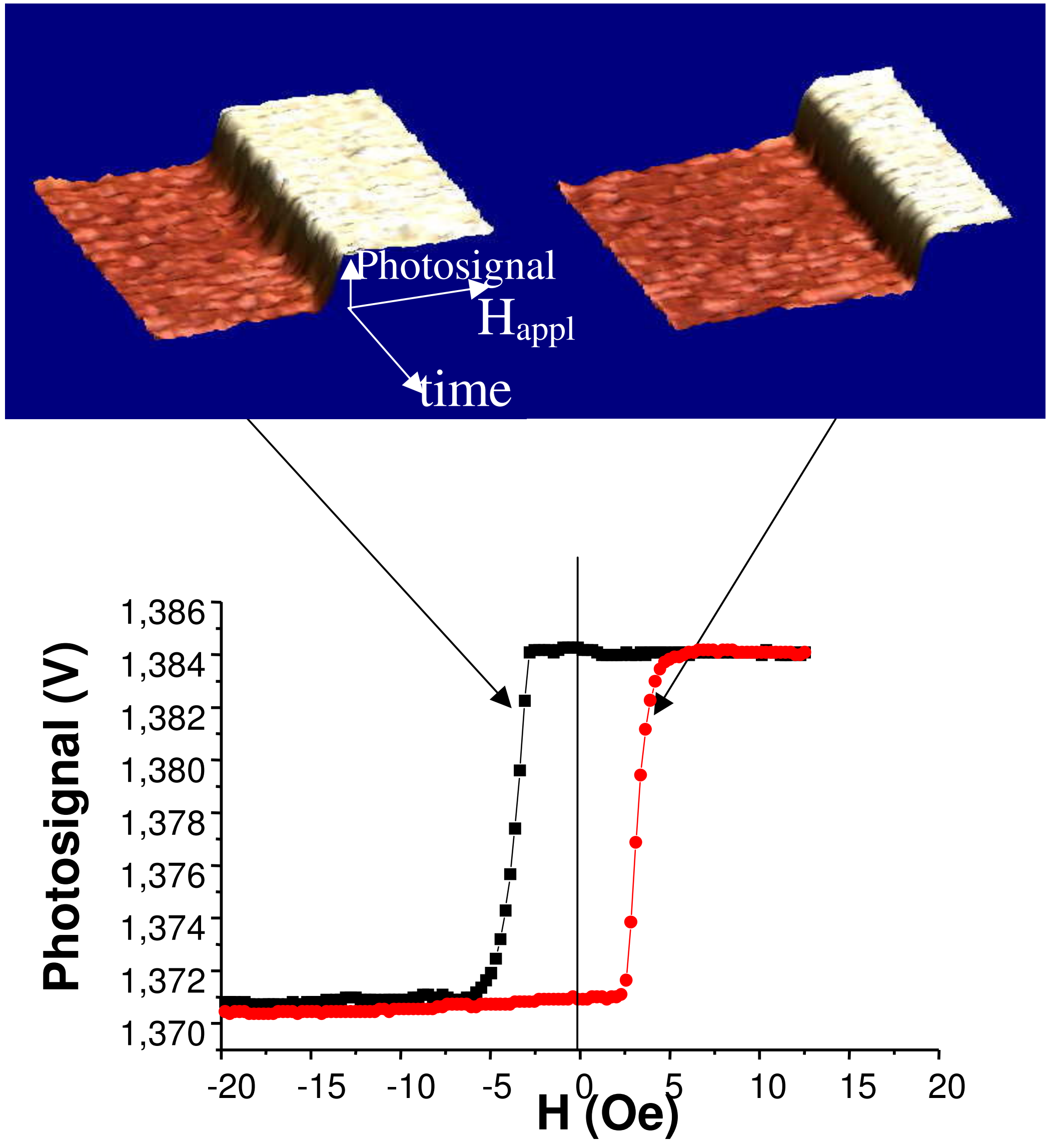
Magneto-optics

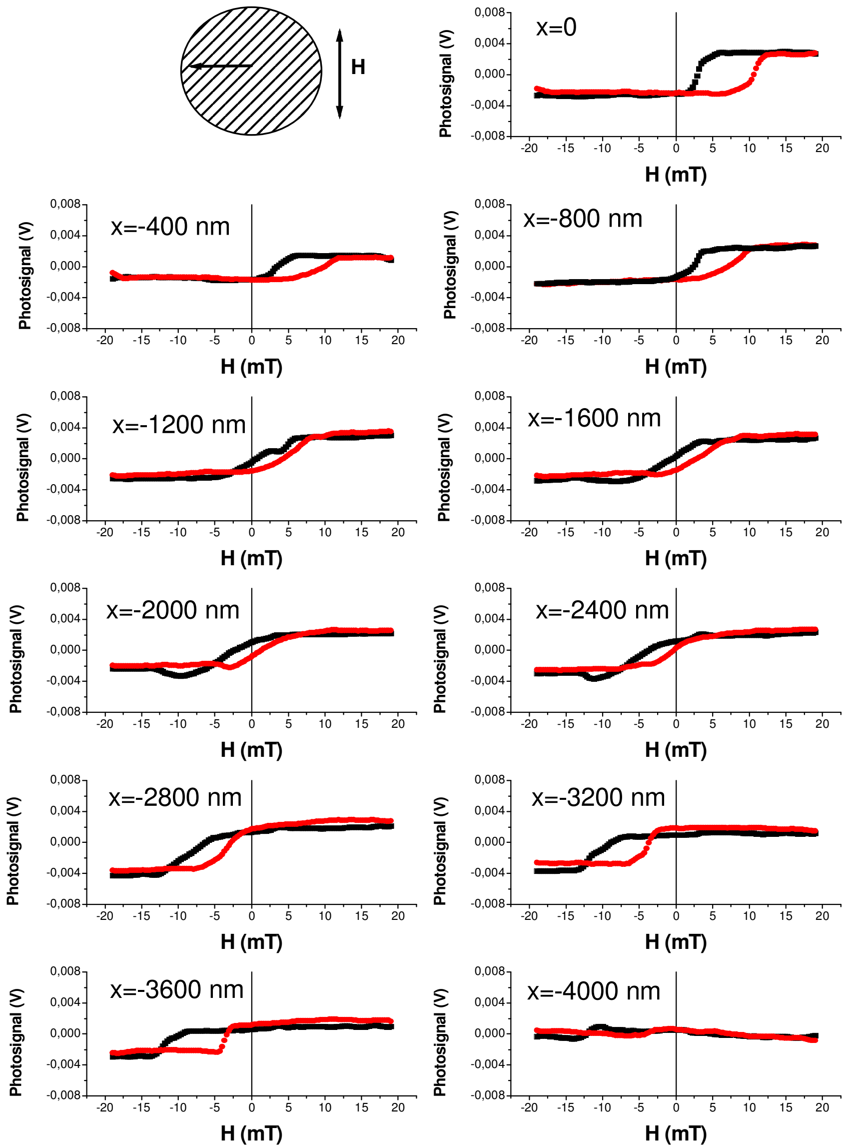


Hysteresis loops

3d mode of WSxM programme
By Nanotec Electrónica (Spain)

Photosignal=f(H_{appl}, time)
N loops (N= 32, 64, 128, …)
Frequency: 0.4 Hz



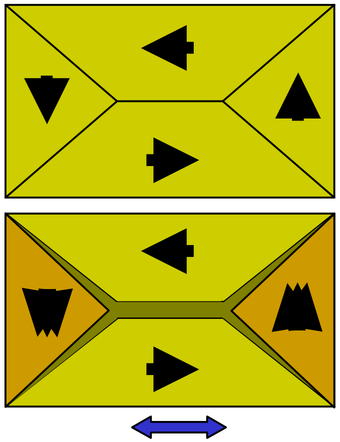


H
x=0
x=-400 nm
x=-800 nm
x=-1200 nm
x=-1600 nm
x=-2000 nm
x=-2400 nm
x=-2800 nm
x=-3200 nm
x=-3600 nm
x=-4000 nm
Photosignal (V)
0,008
0,004
0,000
-0,004
-0,008
H (mT)
-20 -15 -10 -5 0 5 10 15 20

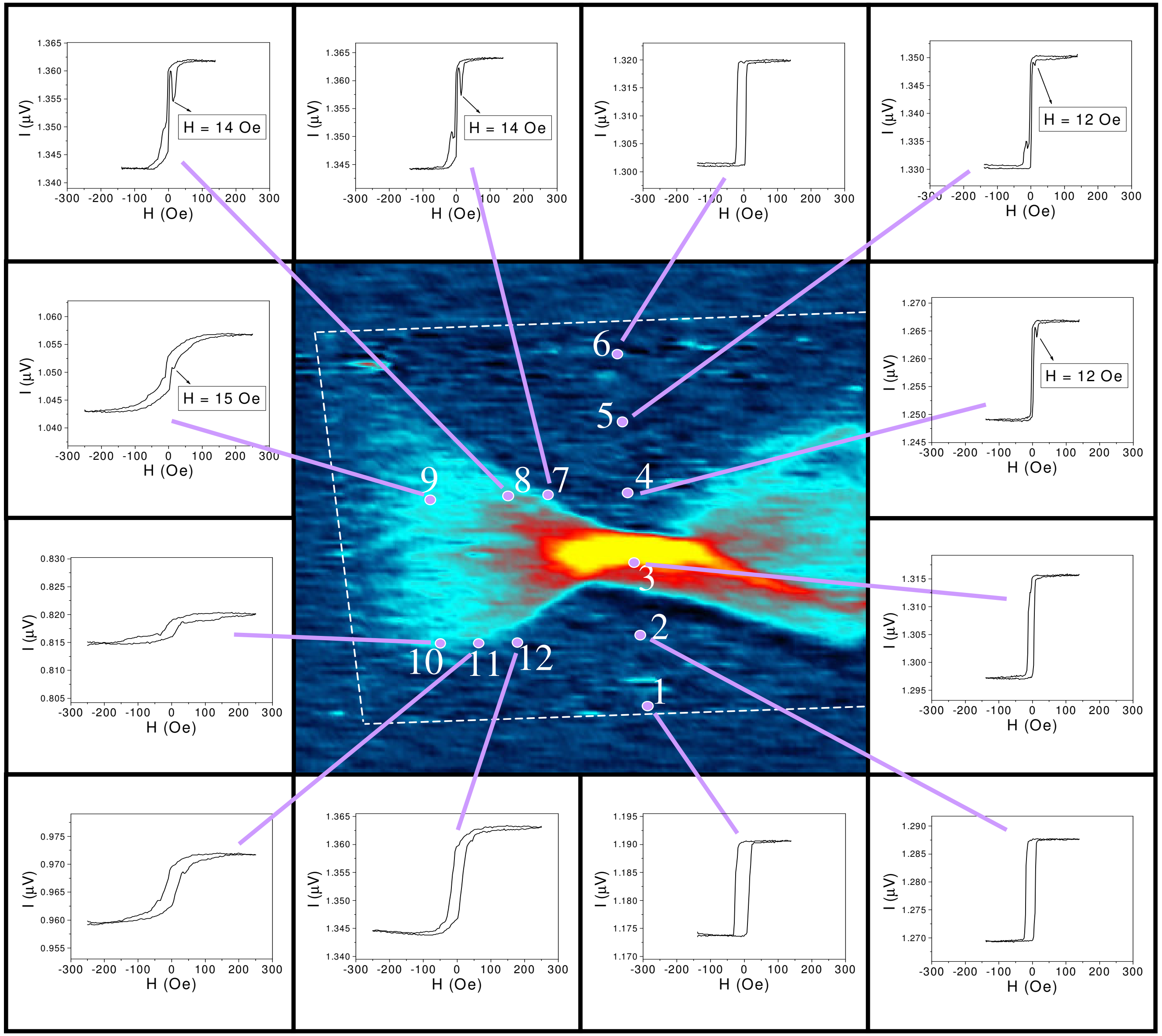
Image and Local hysteresis loops

16 x 16 μm² particle
80 nm thick
$Fe_{4.6}Co_{70.4}Si_{15}B_{10}$

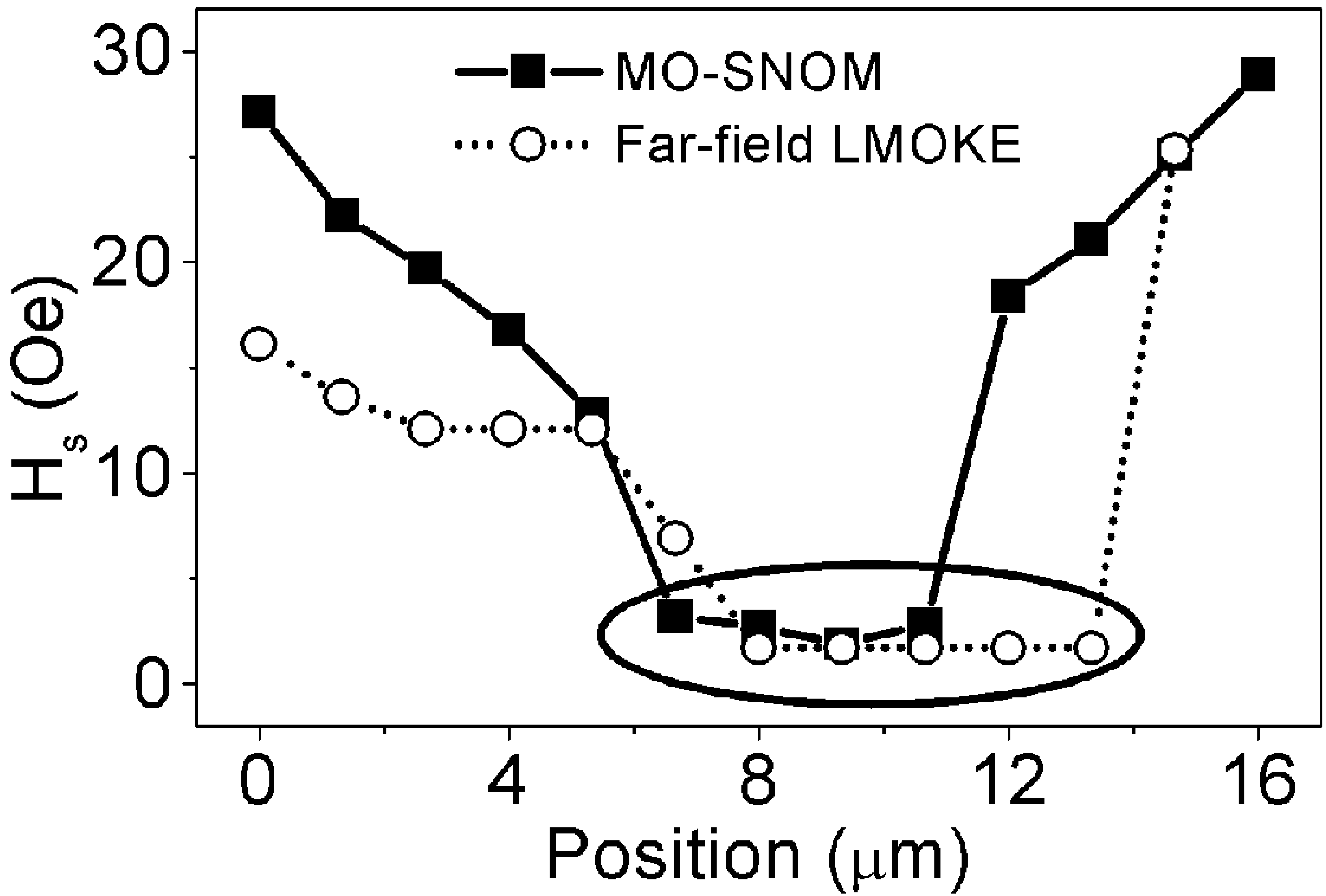
$H_{ac}=0$
$H_{bias}=0$

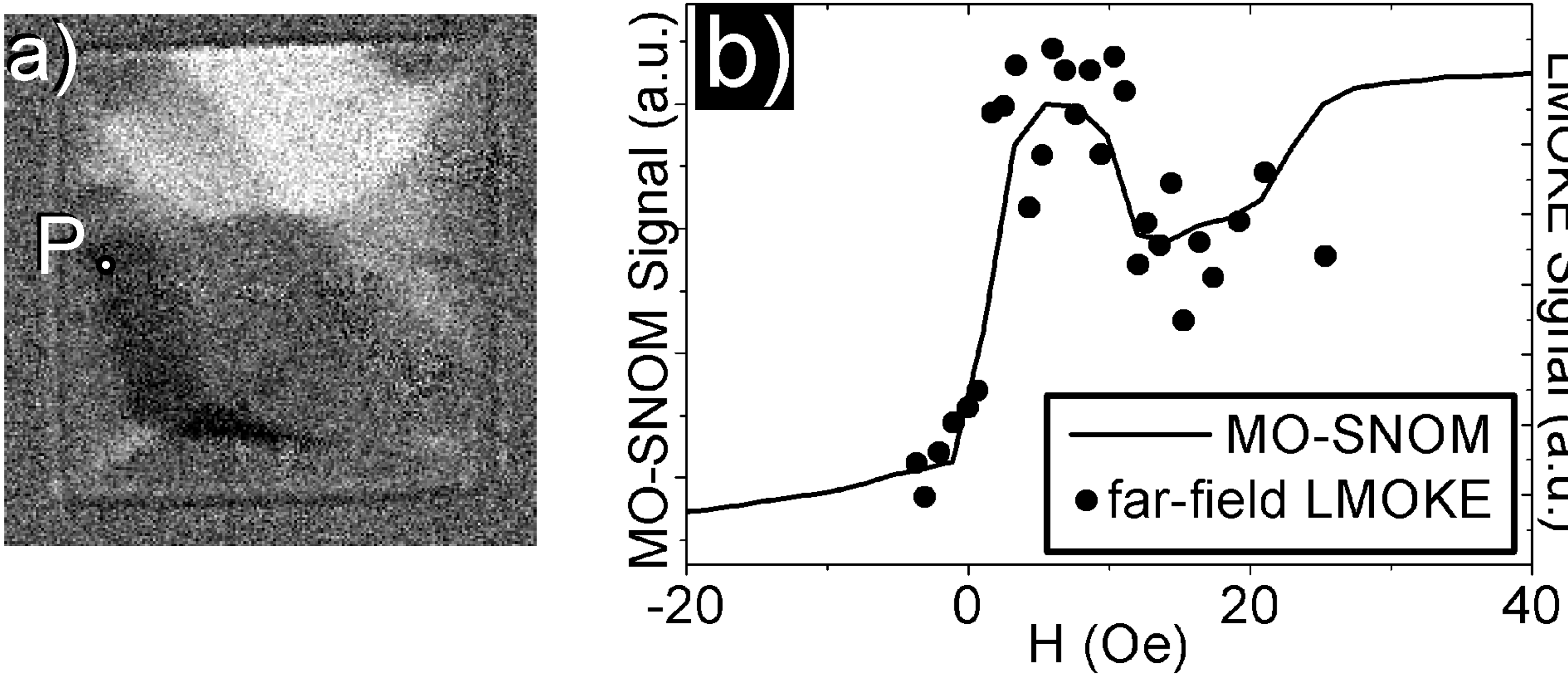


$H_{ac}\neq0$
$H_{bias}=0$



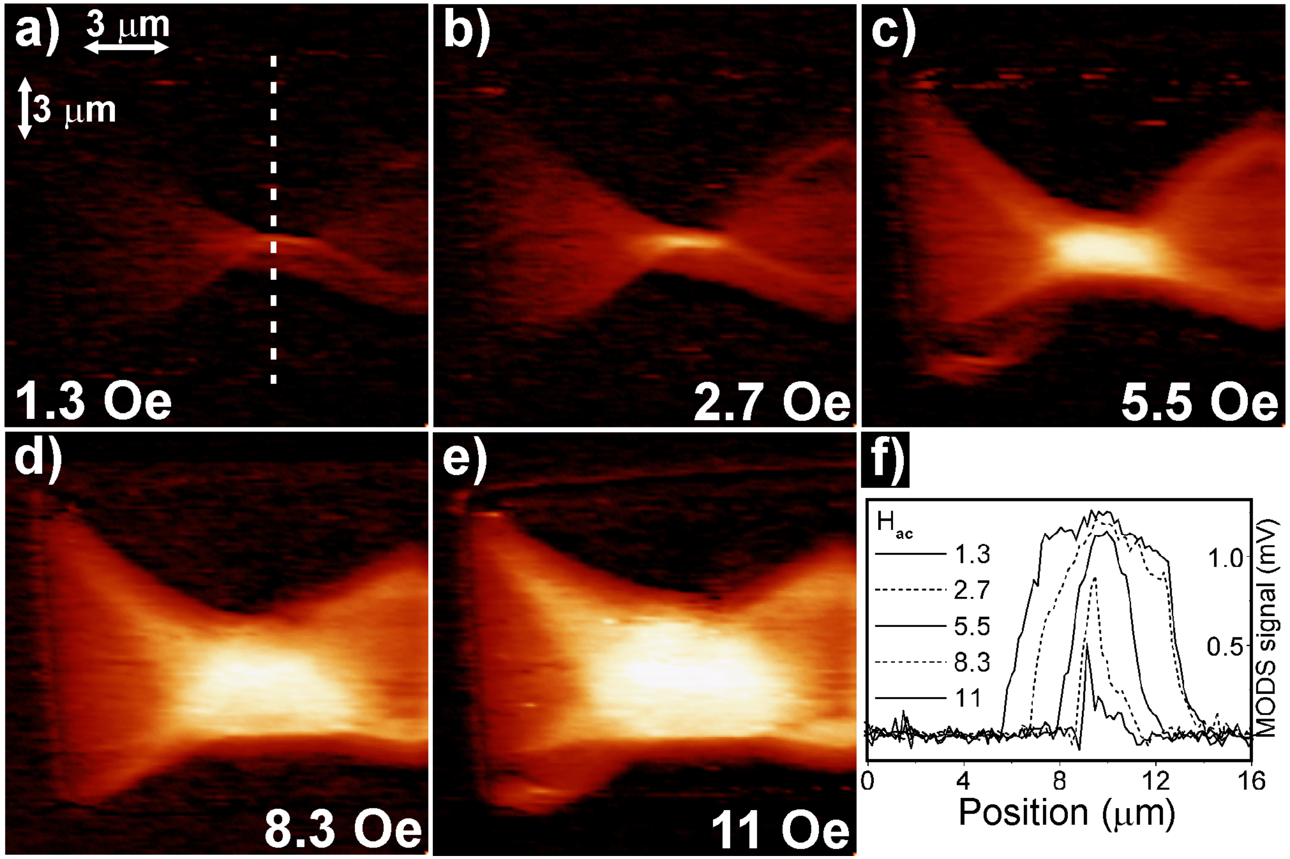
Particular features





a)
P
b)
MO-SNOM Signal (a.u.)
LMOKE Signal (a.u.)
MO-SNOM
far-field LMOKE
-20
0
20
40
H (Oe)

$0.13\ mT < H_{ac} < 1.1\ mT$



16 x 16 μm2 particle
80 nm thick
$Fe_{4.6}Co_{70.4}Si_{15}B_{10}$

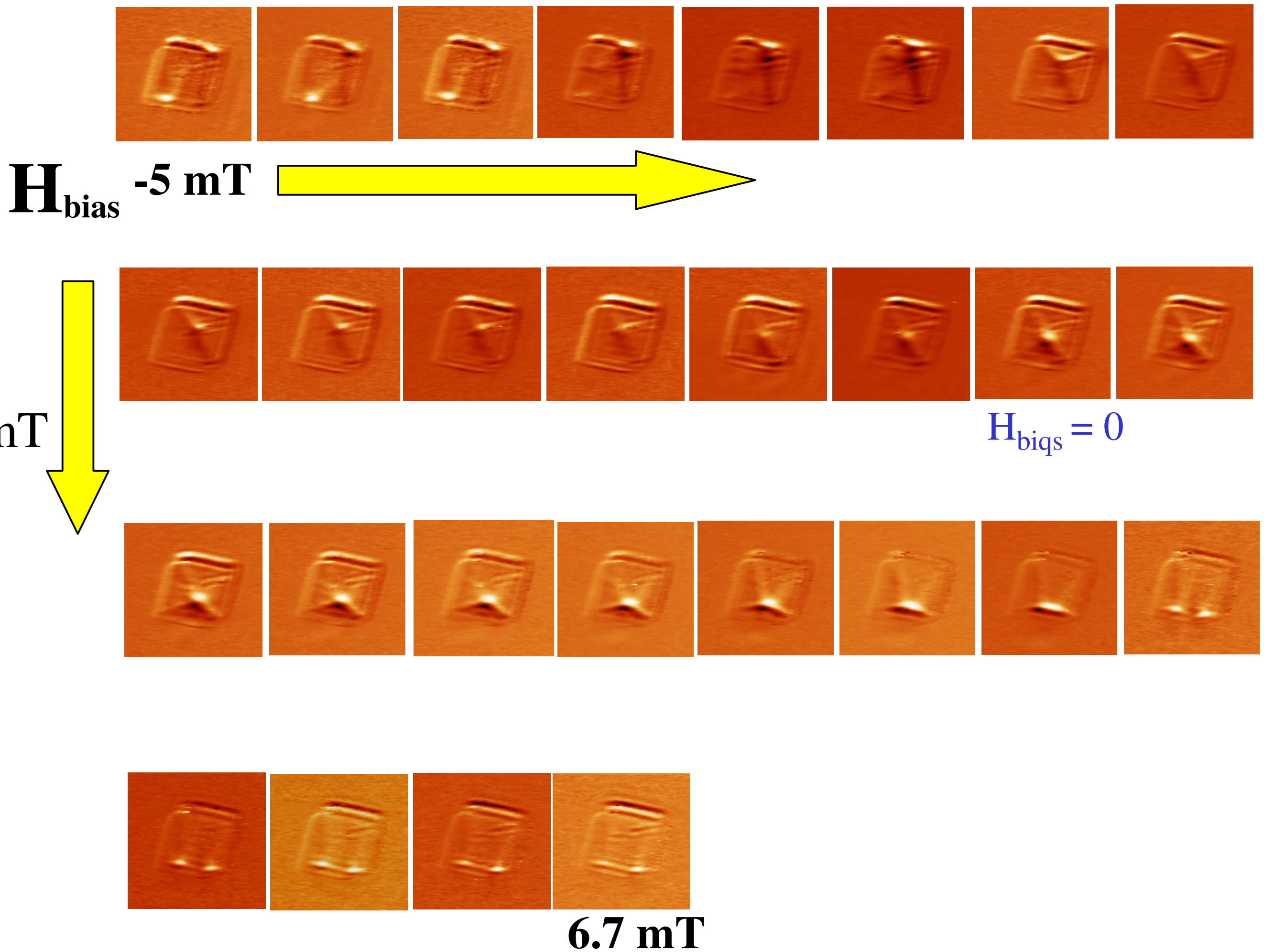
$Fe_{4,6}Co_{70,4}Si_{15}B_{10}$ particle

$4 \times 4\ \mu m^2$; 80 nm thick

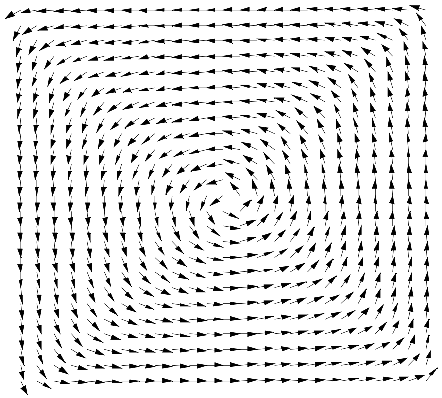
$H_{ac} = 1.1$ mT

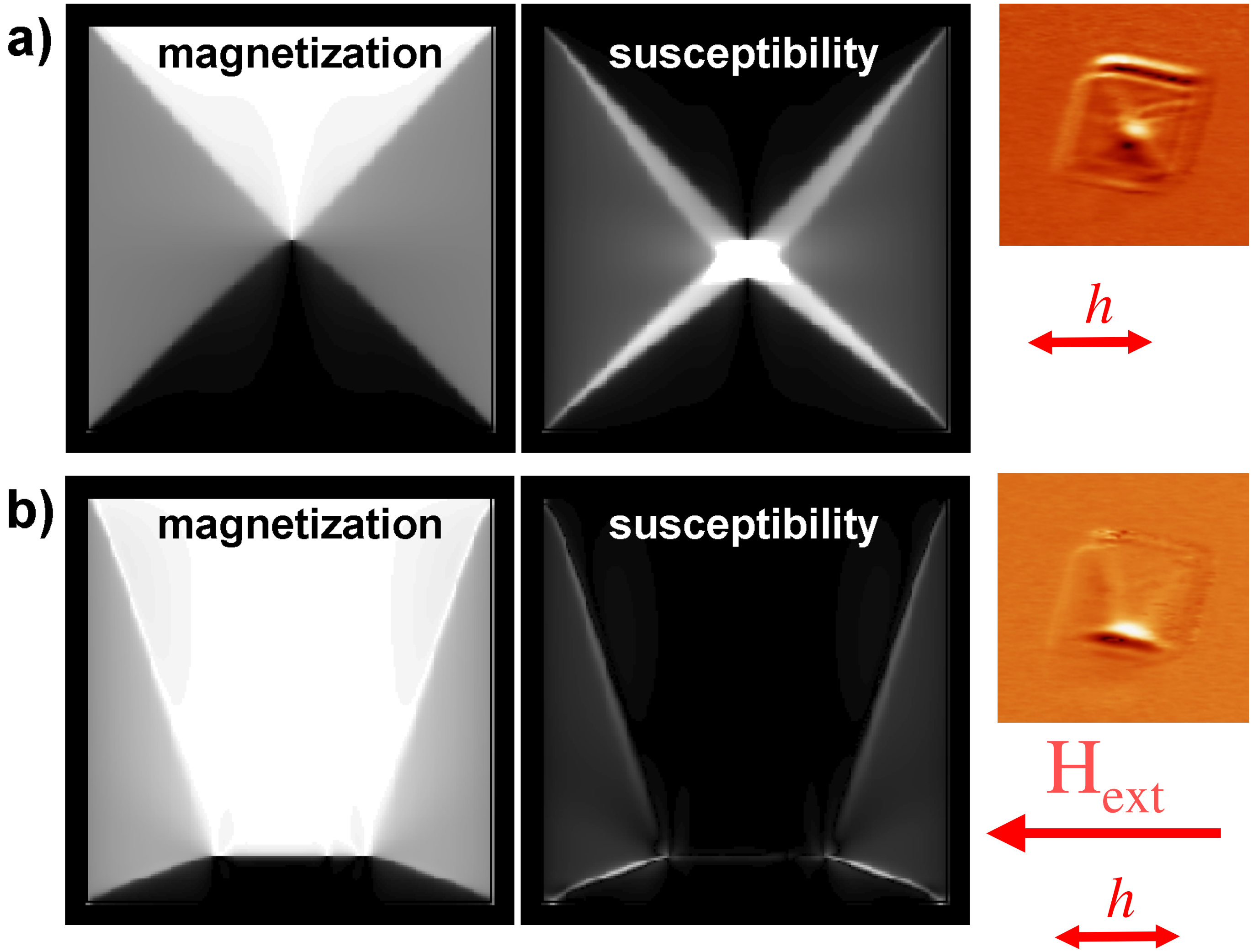
-5 mT<H_{bias}<6.7 mT

Frequency: 0.4 Hz
Image: 256x256



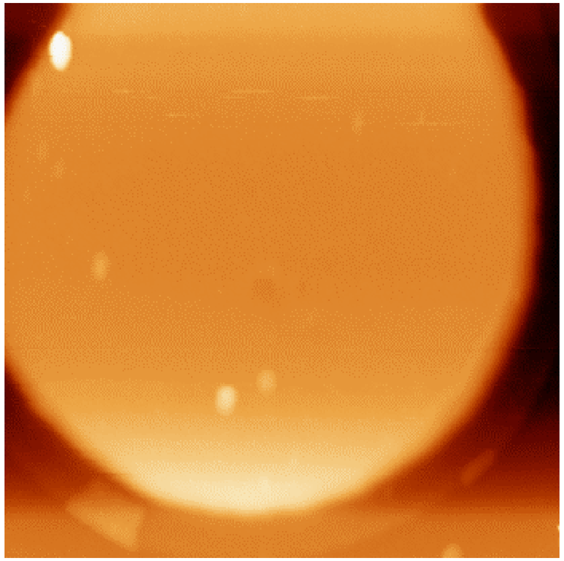
Micromagnetic simulation

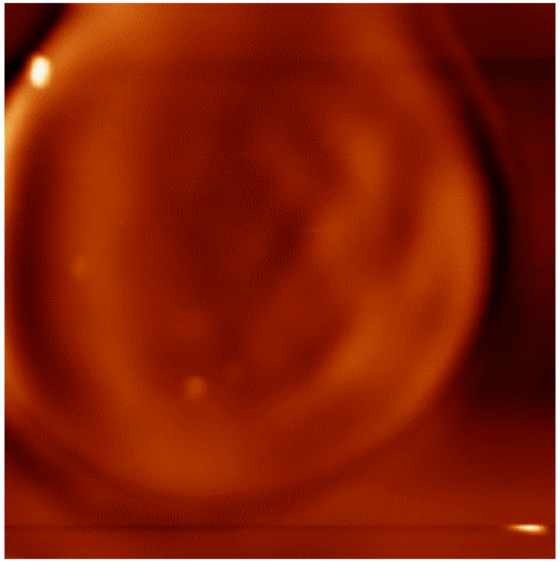


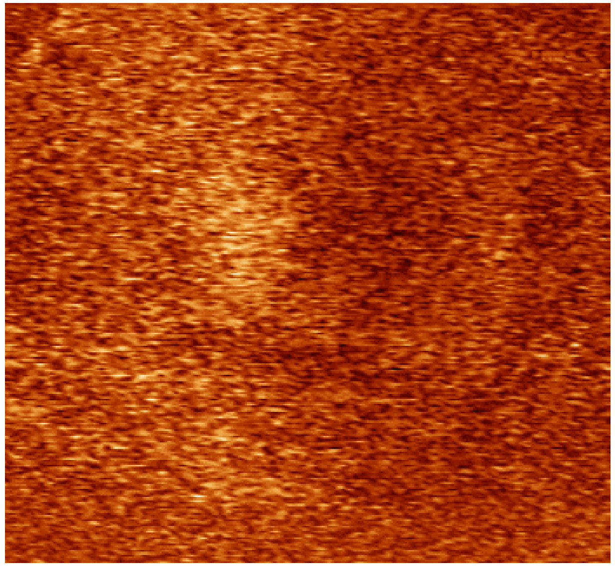


Thin film disk
Ø 5 µm; 50 nm
FeCoSiB

Topography **Optics** **Magneto-optics**

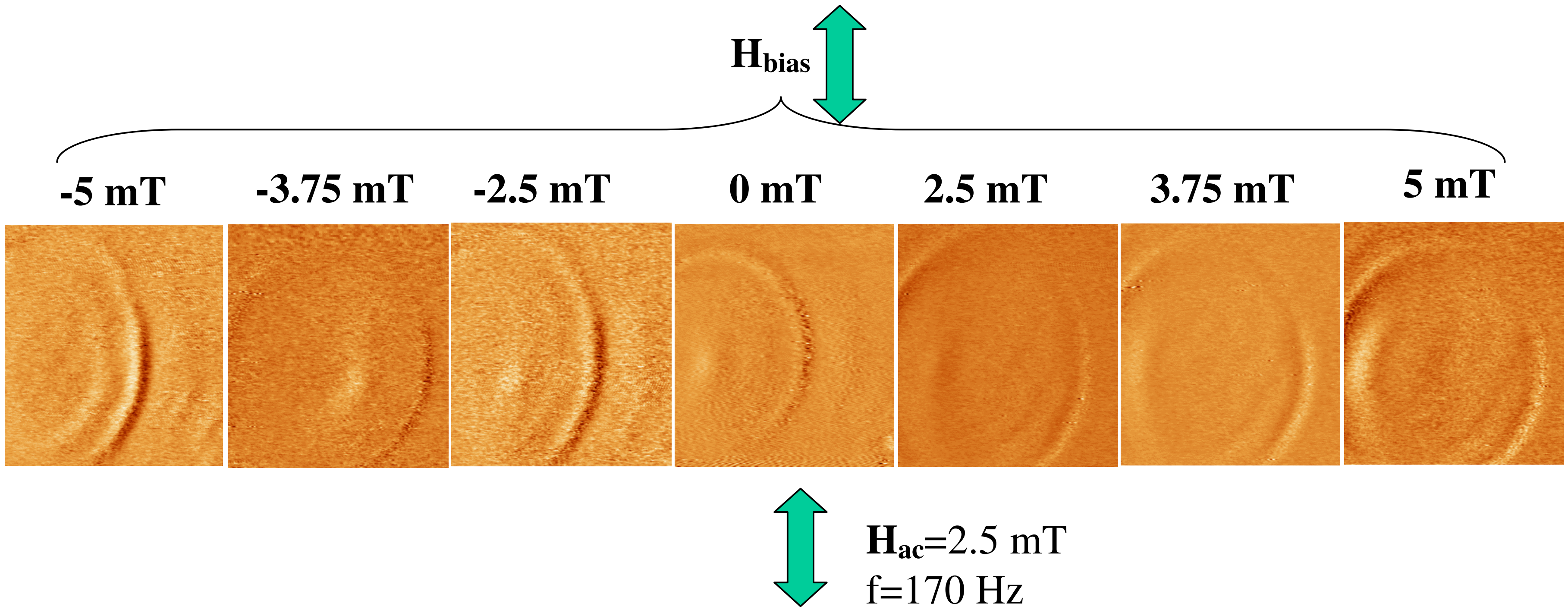




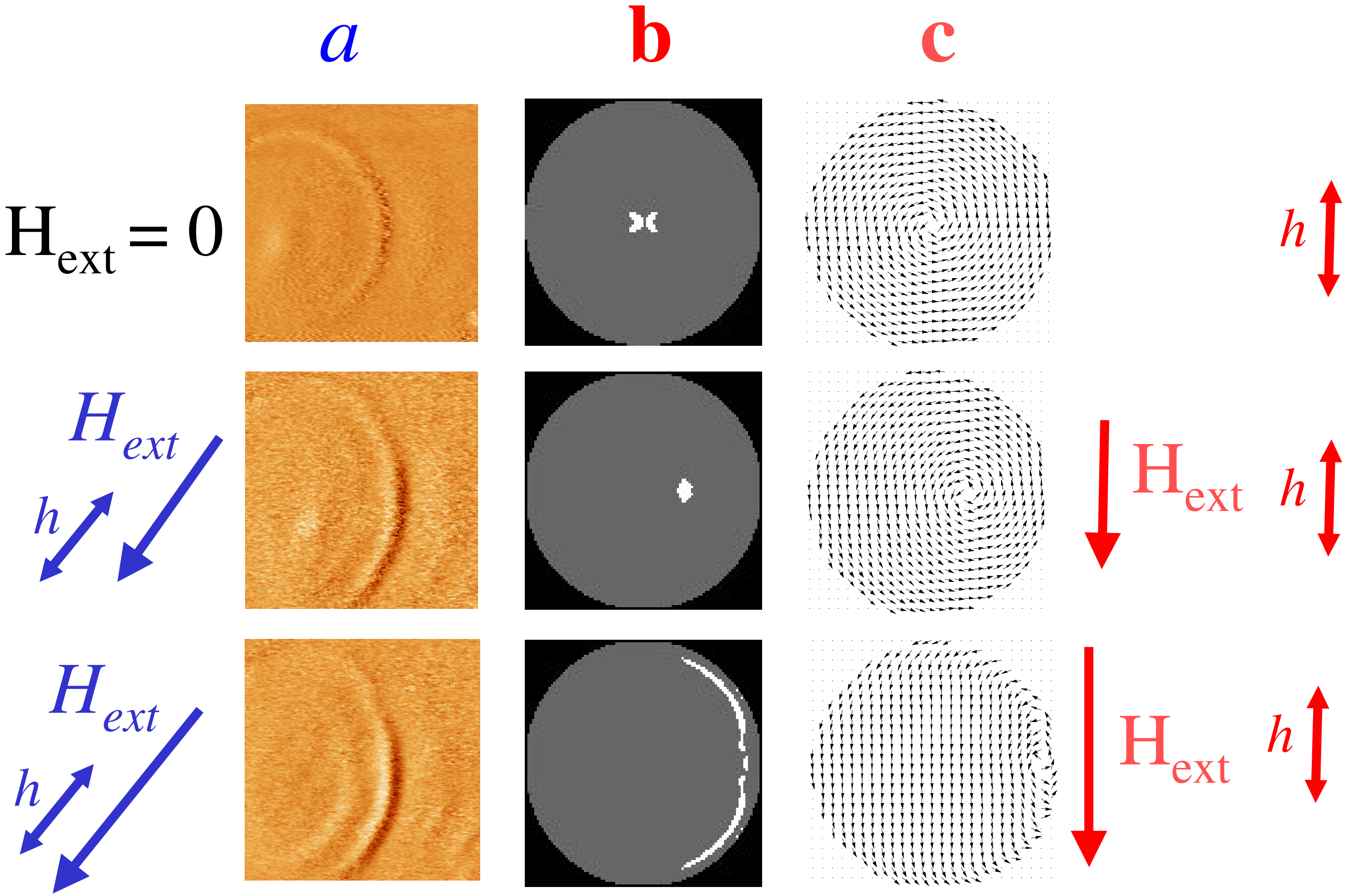


Fe3Si particle

Ø 5 μm; 50 nm thick



Micromagnetic simulation



Resolutions

Topographic: depends on the tip shape

Optical: depends on the size of the nanoaperture and on the tip-sample distance

($\geq$ 20-30 nm)

Magneto-optical: depends on the optical resolution, on the amplitude of H_{ac}

($\approx$ 100 nm)

Outline

* Optical far-field, Rayleigh criterion and Near-field

* Some previous results

* Our experimental method

* Theoretical background

* The experimental set-up

* Some examples

Conclusions

Conclusions

- Near-field optics is sensitive to in-plane components of magnetization
- Transverse Kerr effect is valid in the optical near-field
- The local probe is not magnetic; a bias field can be applied
- Several images can be plotted simultaneously: topographic, optical, magneto-optical
- Local hysteresis loops can be plotted at the nanometre scale
- Slow dynamics of domains can be studied on a elementary pattern
- Resolution depends strongly on the geometrical and optical characteristics of the probe