Functionalization of laser-matter interaction for condensed matter applications

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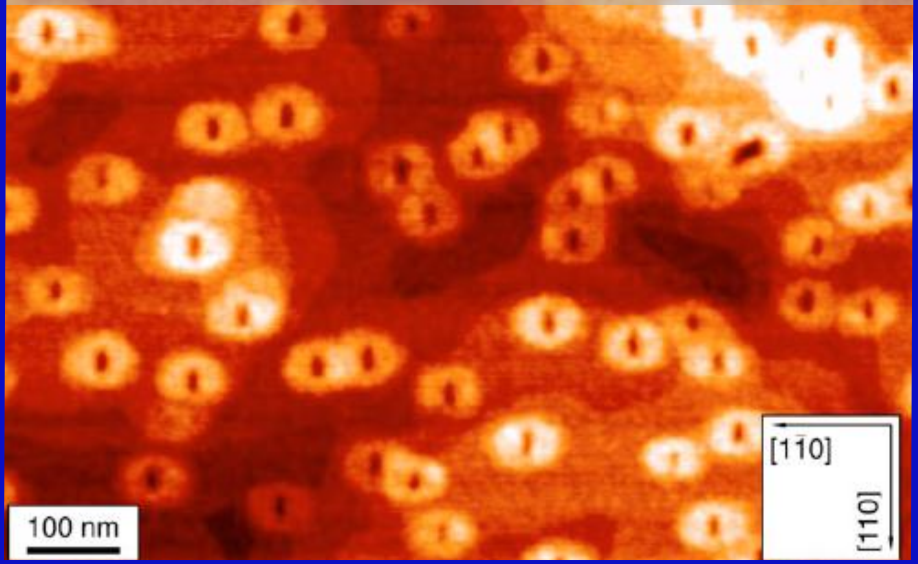
http://qft0.physik.uni-halle.de

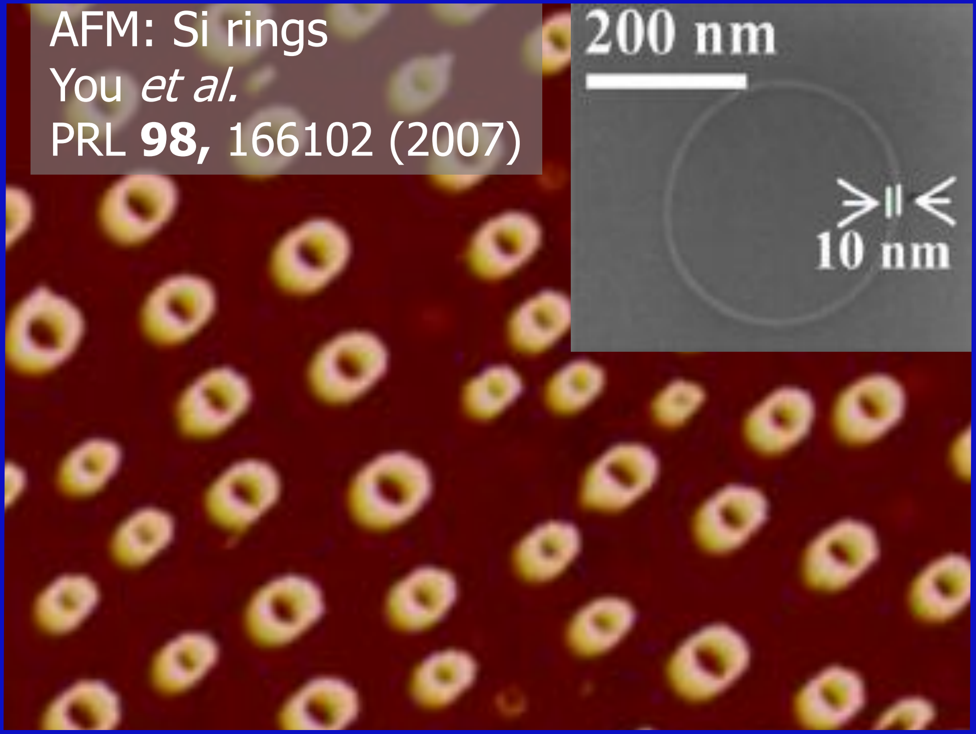
overview

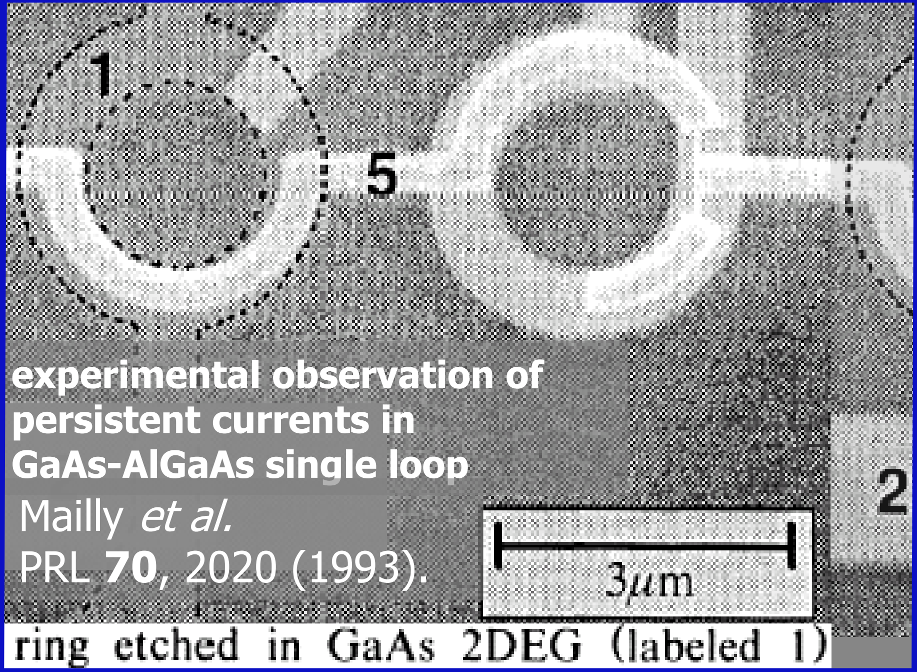
1. experimental status
2. photo-induced polarization and charge currents
3. magnetic pulses: generation and control
4. applications
5. further developments and perspectives

atomic force microscopy (AFM): InAs/GaAs
Offermans *et al.*
Appl. Phys. Lett. **87**, 131902 (2005)



AFM: Si rings
You *et al.*
PRL **98,** 166102 (2007)

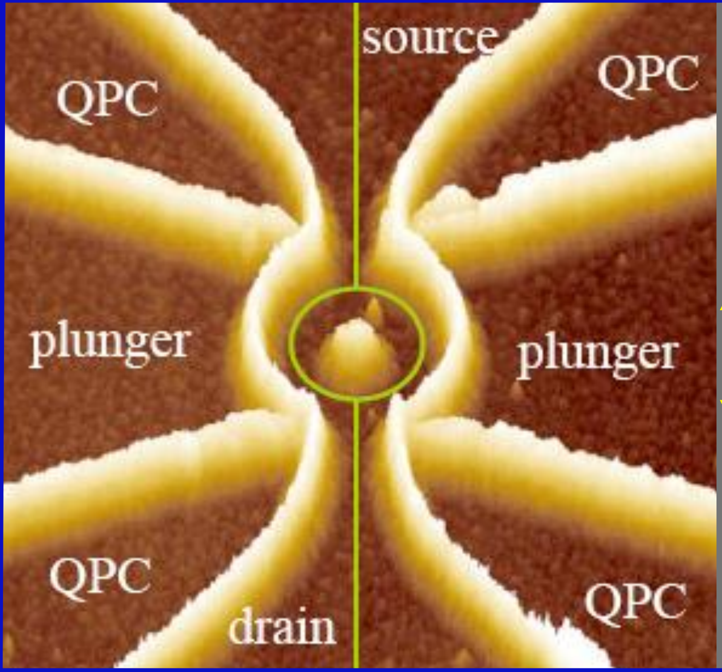




experimental observation of persistent currents in GaAs-AlGaAs single loop

Mailly *et al.*
PRL **70**, 2020 (1993).

ring etched in GaAs 2DEG (labeled 1)

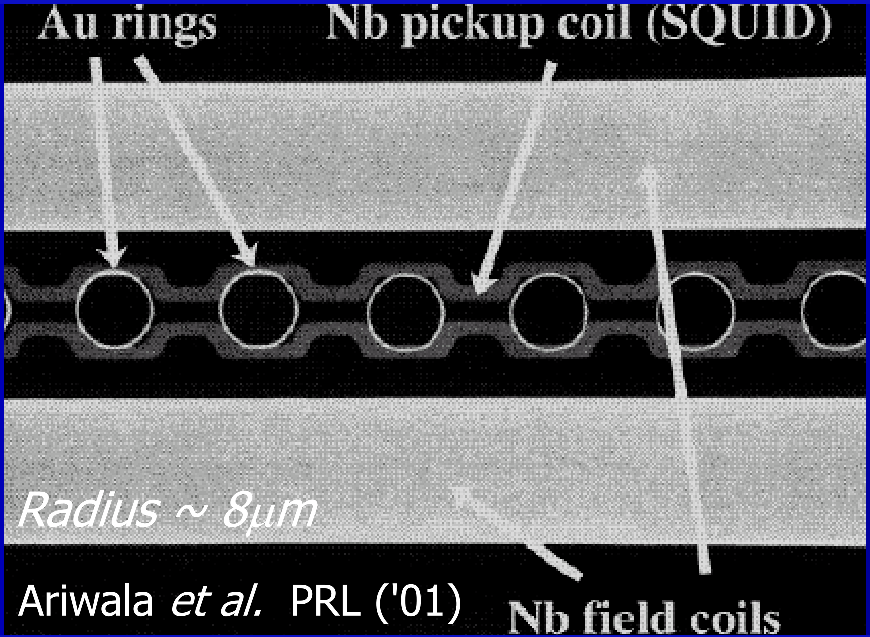


AFM: ring in 2DEG in AlGaAs/GaAs

density
5.10^{11} cm^{-2}

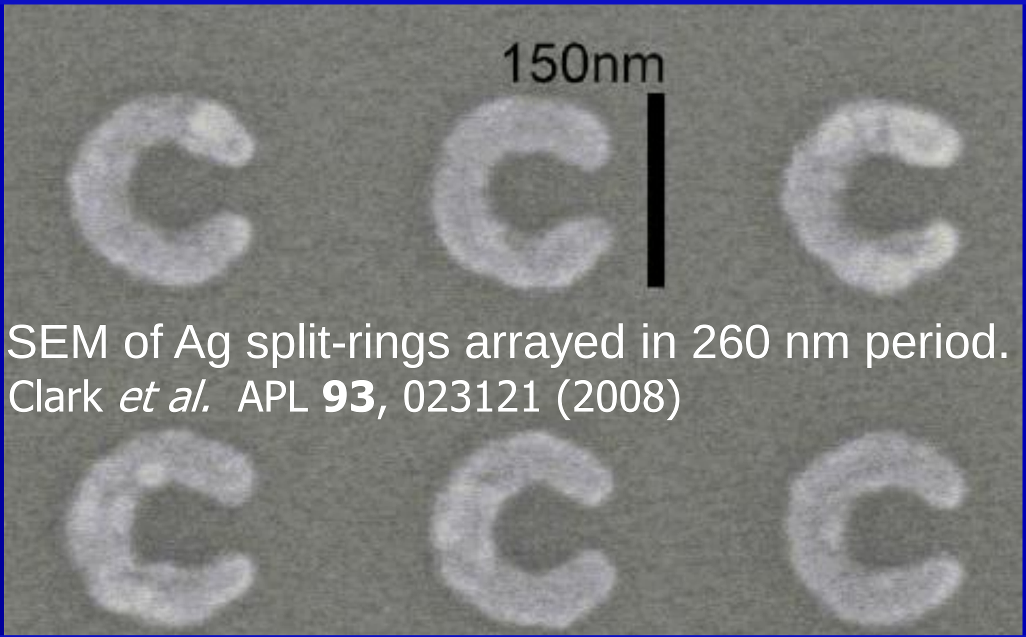
300 nm

Fuhrer *et al.*
Nature
413, 822
(2001)



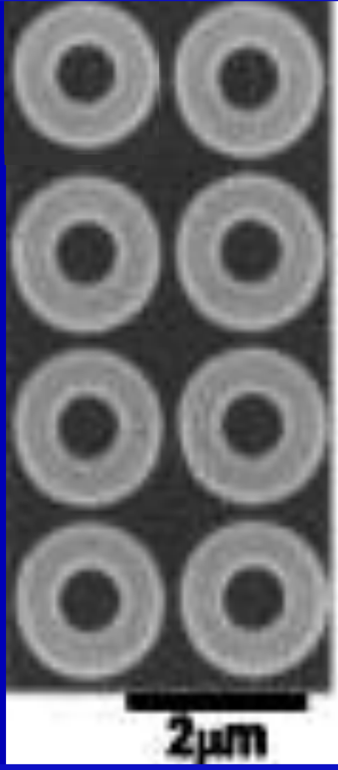
Radius ~ 8μm

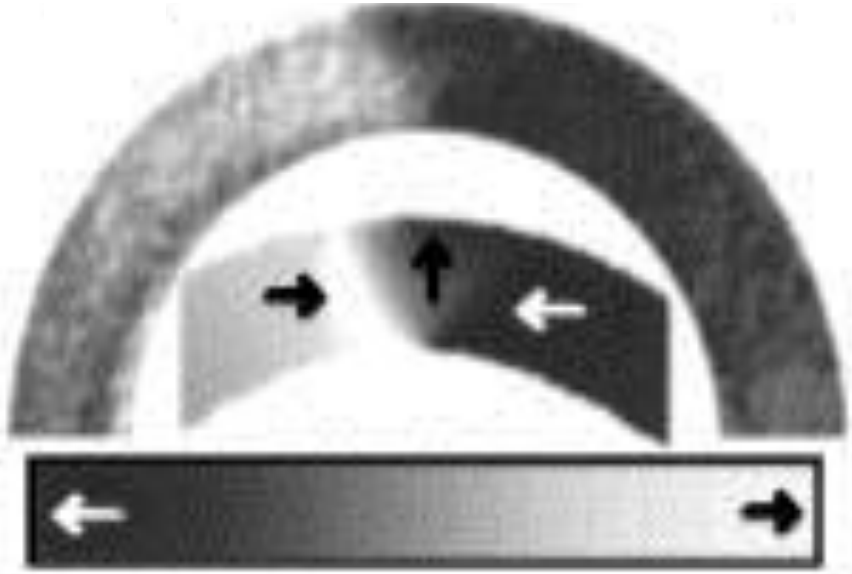
Ariwala *et al.* PRL ('01)

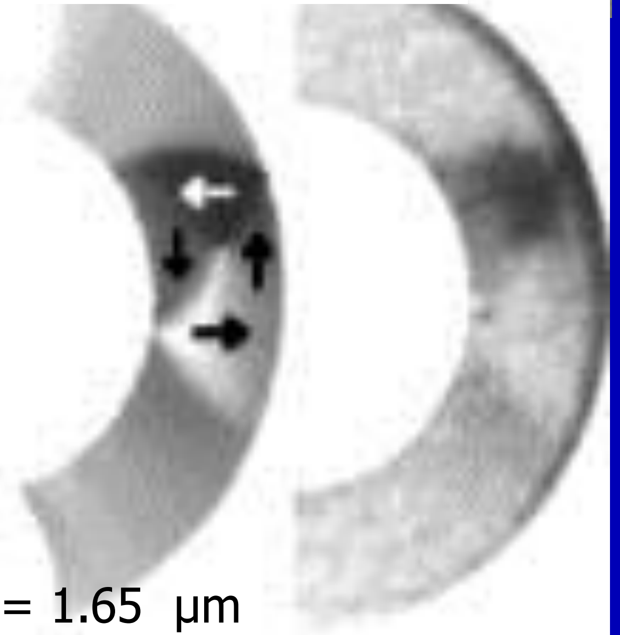


SEM of Ag split-rings arrayed in 260 nm period.
Clark *et al.* APL **93**, 023121 (2008)

Kläui *et al.* APL **85**, 5637 (`04); PRL **94**, 106601 (`05)

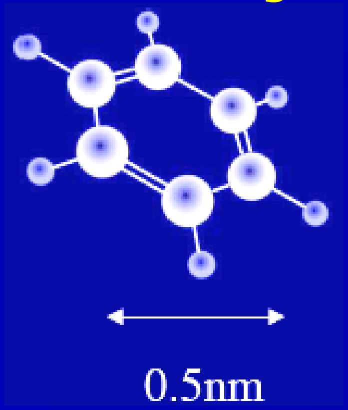


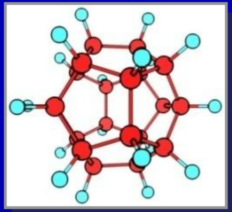




polycrystalline Co rings outer diameter = 1.65 μm
width = 530 nm; thickness = 34 nm

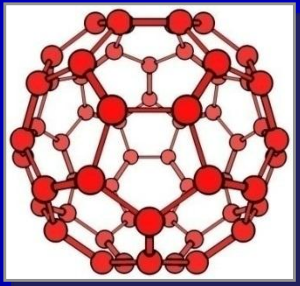
benzene ring



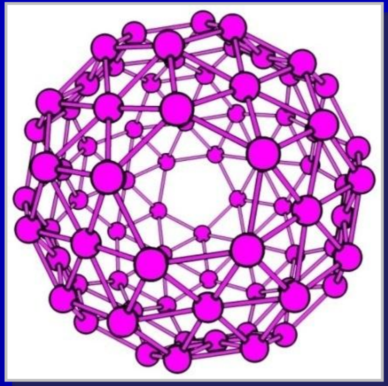


dodecahedrane

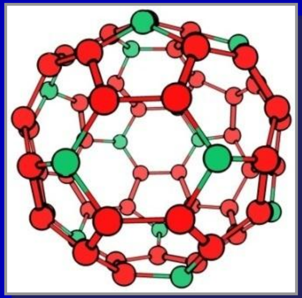
$C_{20}H_{20}$



C_{60}

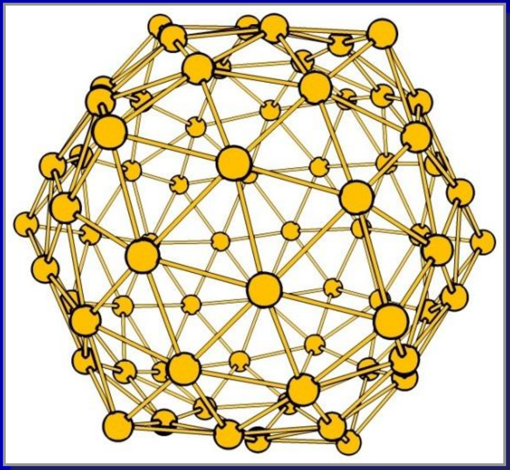


B_{80}

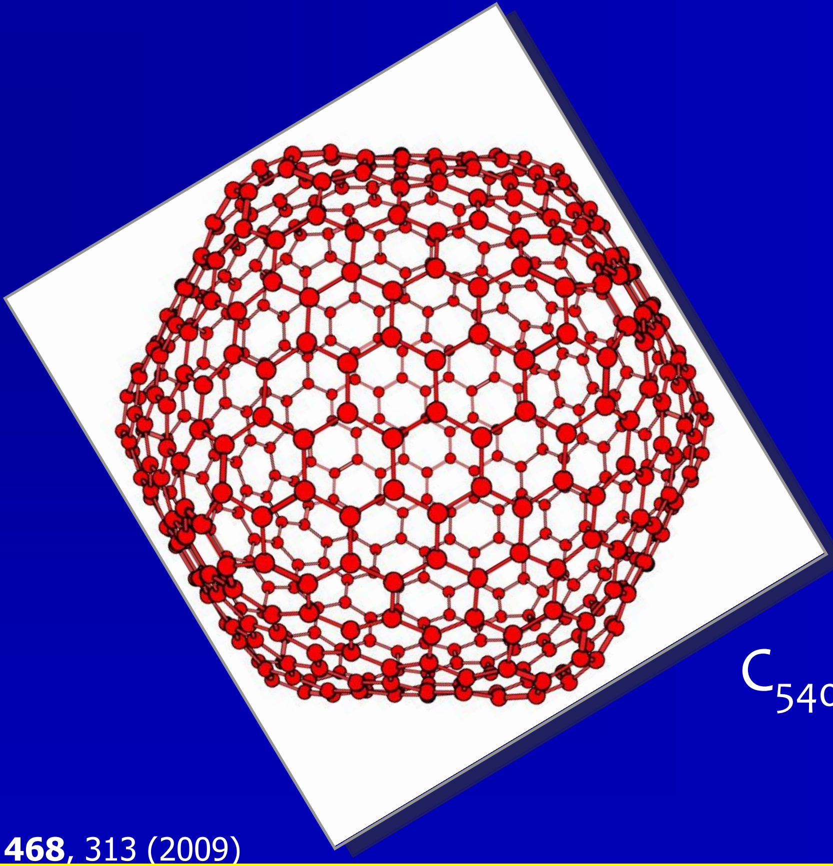


dodeca-aza[60] fullerene

$C_{48}N_{12}$



Au_{72}



C_{540}

Pavlyukh, Berakdar Chem. Phys. Lett. **468**, 313 (2009)

persistent currents

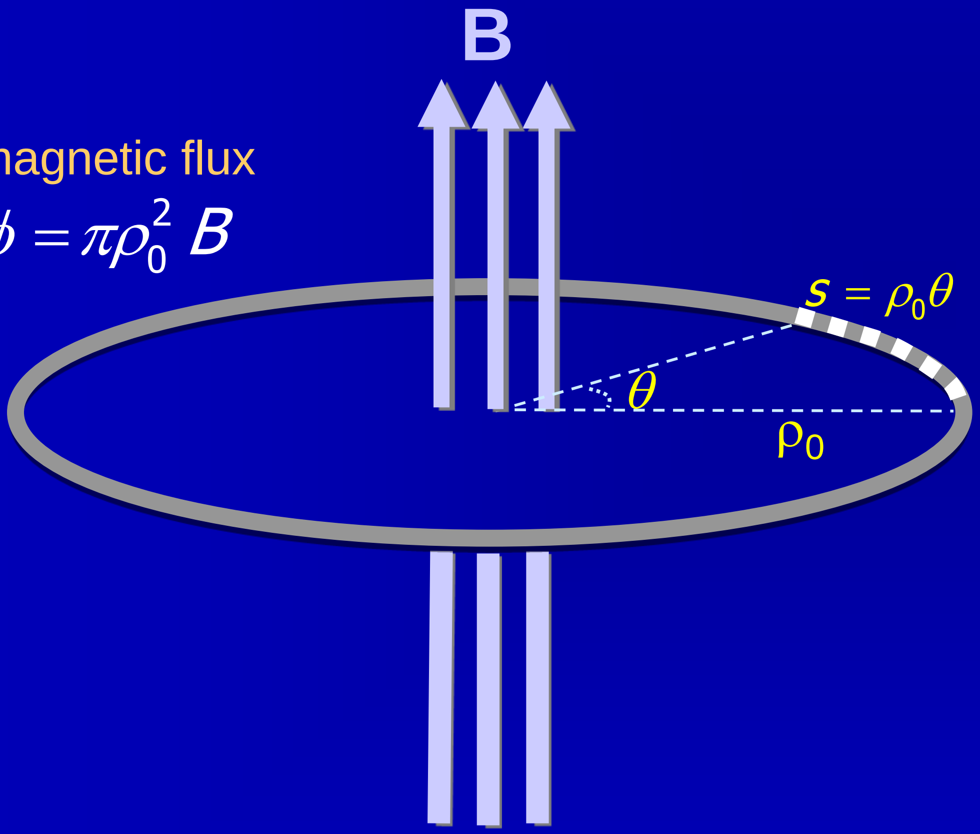
stationary single particle states

$$\psi(s) = \frac{1}{\sqrt{L}} \quad e^{i\,\bar{k}_m s}$$

$$\boxed{\psi(\theta) = \frac{1}{\sqrt{L}} \quad e^{i\,\bar{k}_m s} \quad e^{-i\,\theta\,\phi/\phi_0}}$$

magnetic flux

$$\phi = \pi\rho_0^2\, B$$



Aharonov-Bohm geometry

$$E_m = \frac{\hbar^2 k_m^2}{2m*}, \quad k_m = \frac{2\pi}{L}\left(m + \frac{\phi}{\phi_0}\right)$$

$$v_m = \frac{\hbar}{m*}\frac{2\pi}{L}(m + \phi/\phi_0)$$

$$I_m \approx \frac{e v_m}{L}$$

$$v_m = -v_{-m} \Rightarrow I_m + I_{-m} = 0$$

$$\phi \approx \phi_0 \Rightarrow v_m \neq -v_{-m} \Rightarrow \quad B \approx \frac{\phi_0}{\pi\rho_0^2}$$

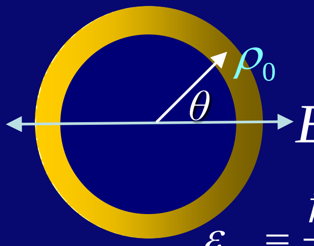
➔ Benzene ring → B~5000 T
Mailly et al. 1993 → **I~ 4 nA**

density- matrix formalism

Moskalenko, Berakdar PRB **70**, 161303 **(R)** (´06); Rossi & Kuhn, *Rev. Mod. Phys.* 74, 895 (2002)

single-particle density matrix $\rho_{m,m'} = \langle m|\hat{\rho}|m'\rangle = \mathrm{Tr}[\hat{\Sigma}\hat{a}^{\dagger}_{m}\hat{a}_{m'}] \equiv \langle \hat{a}^{\dagger}_{m}\hat{a}_{m'}\rangle$

$$\boxed{\hat{H}_{\mathrm{tot}} = \hat{H}_0^{\mathrm{carr}} + \hat{H}_0^{\mathrm{phon}} + \hat{H}_{\mathrm{C}} + \hat{H}_{\mathrm{P}} + \hat{V}}$$



$$\varepsilon_m = \frac{\hbar^2 k_m^2}{2m^*}$$

$$\hat{H}_0^{\mathrm{carr}} = \sum_m \varepsilon_m \hat{a}^{\dagger}_m \hat{a}_m \qquad \hat{H}_0^{\mathrm{phon}} = \sum_{\vec{q}} \hbar\omega_{\vec{q}} \left(b^{\dagger}_{\vec{q}} b_{\vec{q}} + \frac{1}{2} \right)$$

$$\hat{H}_C = \frac{1}{2} \sum_{m_1,m_2,m} V_m \; \hat{a}^{\dagger}_{m_1} \hat{a}^{\dagger}_{m_2} \hat{a}_{m_2+m} \hat{a}_{m_1-m}$$

– electron-electron interaction

$$\hat{H}_P = \sum_{\vec{q},m,m'} G^{m'}_{\vec{q}} b_{\vec{q}} \, a^{\dagger}_m a_{m-m'} + \mathrm{h.c.}$$

– electron-phonon interaction

$$\hat{V} = -eE(t)\,\rho_0 \sum_{m,m'} \langle m|\cos\theta|m'\rangle a^{\dagger}_m a_{m'}$$

– interaction with light field

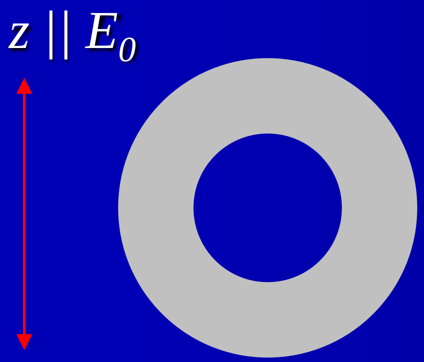
$$\langle \hat{O} \rangle = tr[\hat{O}\hat{\rho}(t)]$$

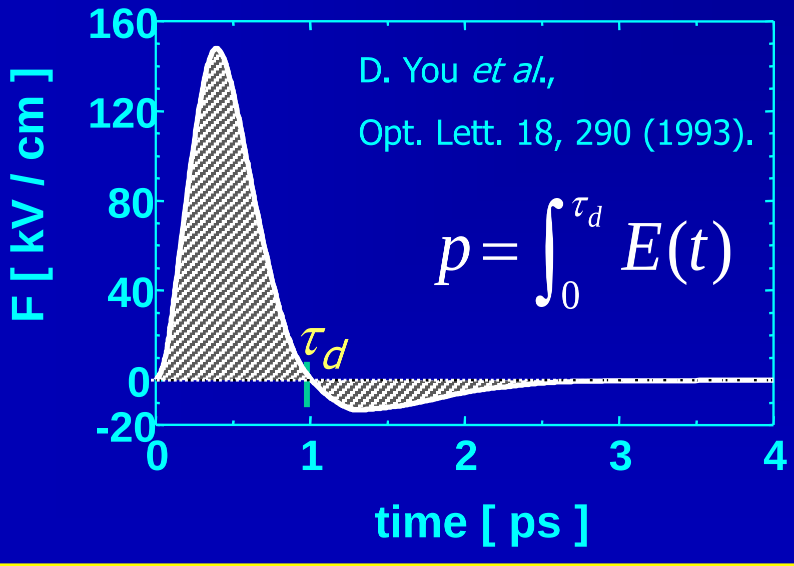
Heisenberg equations of motion ⇨ hierarchy problem ⇨ truncation scheme ⇨ closed system of ODE's

pulse-induced dynamics

single-cycle pulses

$$m\ddot{z} = -p\,\delta(t) \quad \Rightarrow \begin{cases} \dot{z} = \dfrac{-p}{m} + \dot{z}_0 & \text{for } t > 0 \\ \dot{z} = \dot{z}_0 & \text{for } t < 0 \end{cases}$$





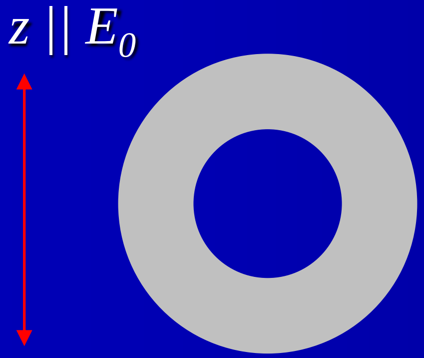
D. You *et al*.,
Opt. Lett. 18, 290 (1993).

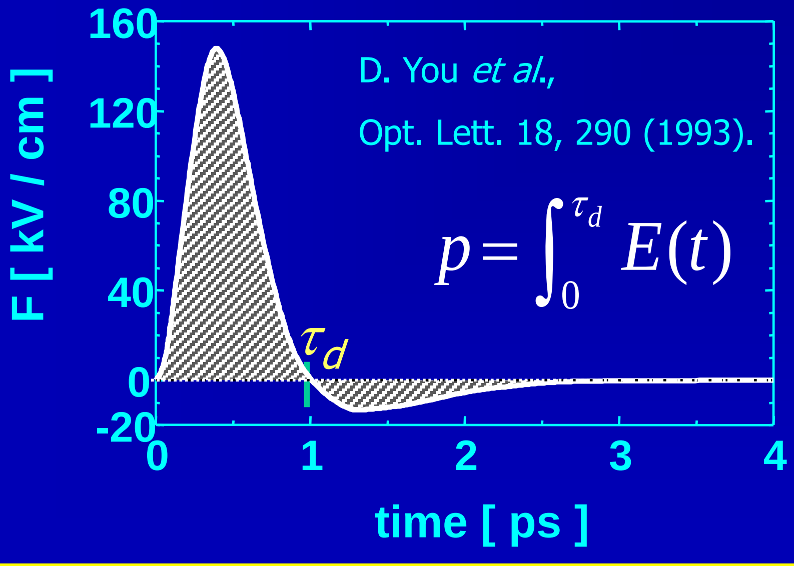
$$p = \int_0^{\tau_d} E(t)$$

pulse-induced dynamics

single-cycle pulses

$$m\ddot{z} = -p\,\delta(t) \;\Rightarrow\; \begin{cases} \dot{z} = \dfrac{-p}{m} + \dot{z}_0 & \text{for } t > 0 \\ \dot{z} = \dot{z}_0 & \text{for } t < 0 \end{cases}$$



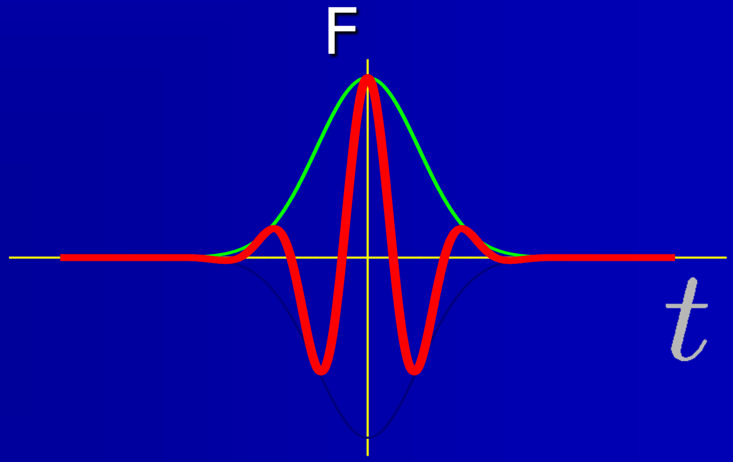


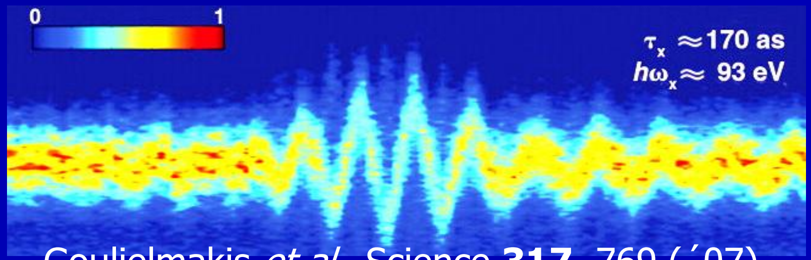
D. You *et al.*,

Opt. Lett. 18, 290 (1993).

$$p = \int_0^{\tau_d} E(t)$$

few-cycle pulses





Goulielmakis *et al.*, Science **317**, 769 (´07)

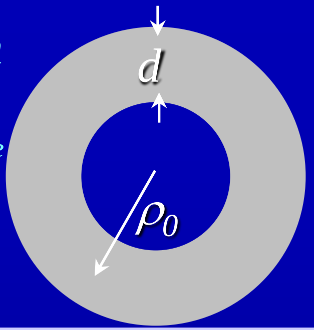
induced dipole moment

$\rho_0 = 1.35\ \mu m$

$m^* = 0.067 m_e$

$N = 1400$

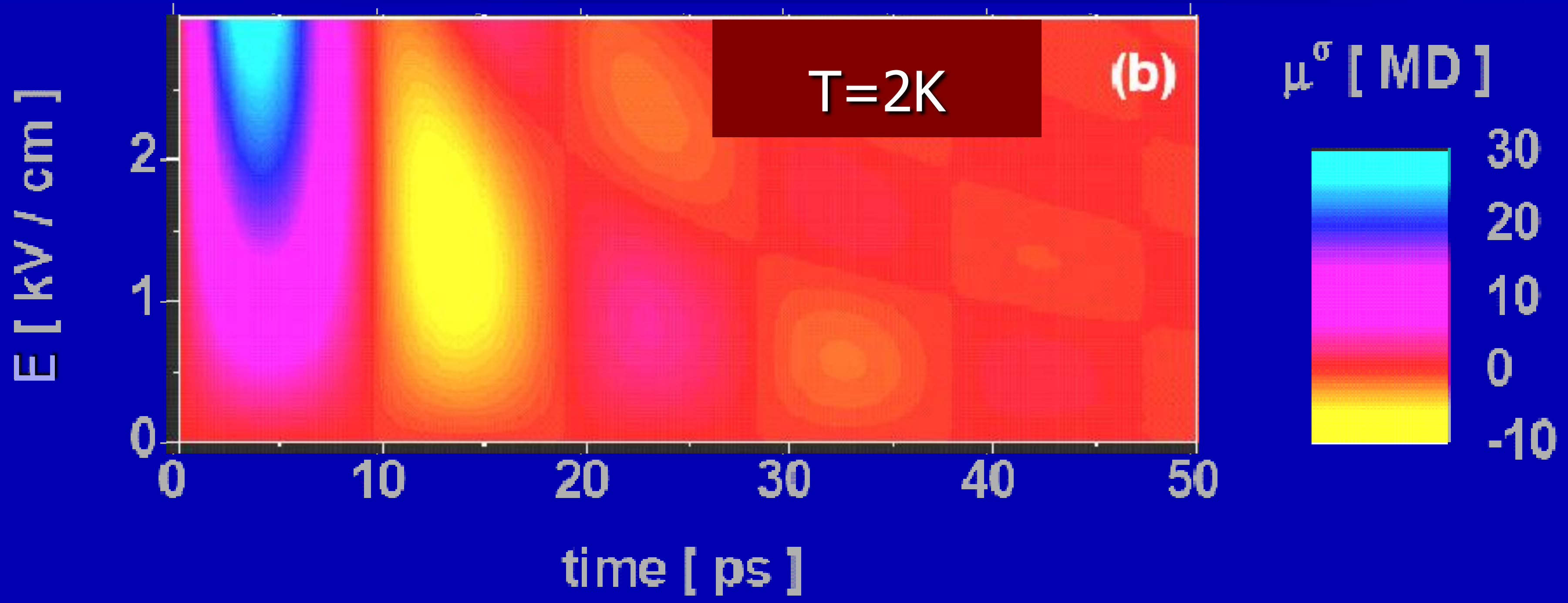
$d = 160\ nm$



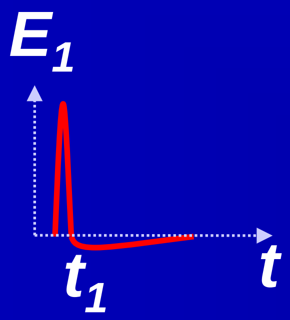
Mailly *et al.*
PRL **70**, 2020 (´93)

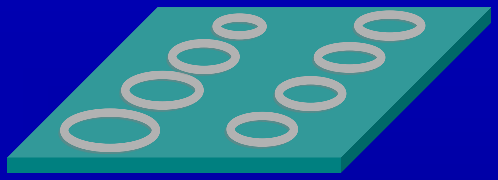
$$\vec{\mu} = tr[e\hat{r}\,\hat{\rho}(t)], \quad \mu_{||} = er_0 \sum_m \mathrm{Re}[\rho_{m+1,m}], \quad \mu_{\perp} = er_0 \sum_m \mathrm{Im}[\rho_{m+1,m}]$$

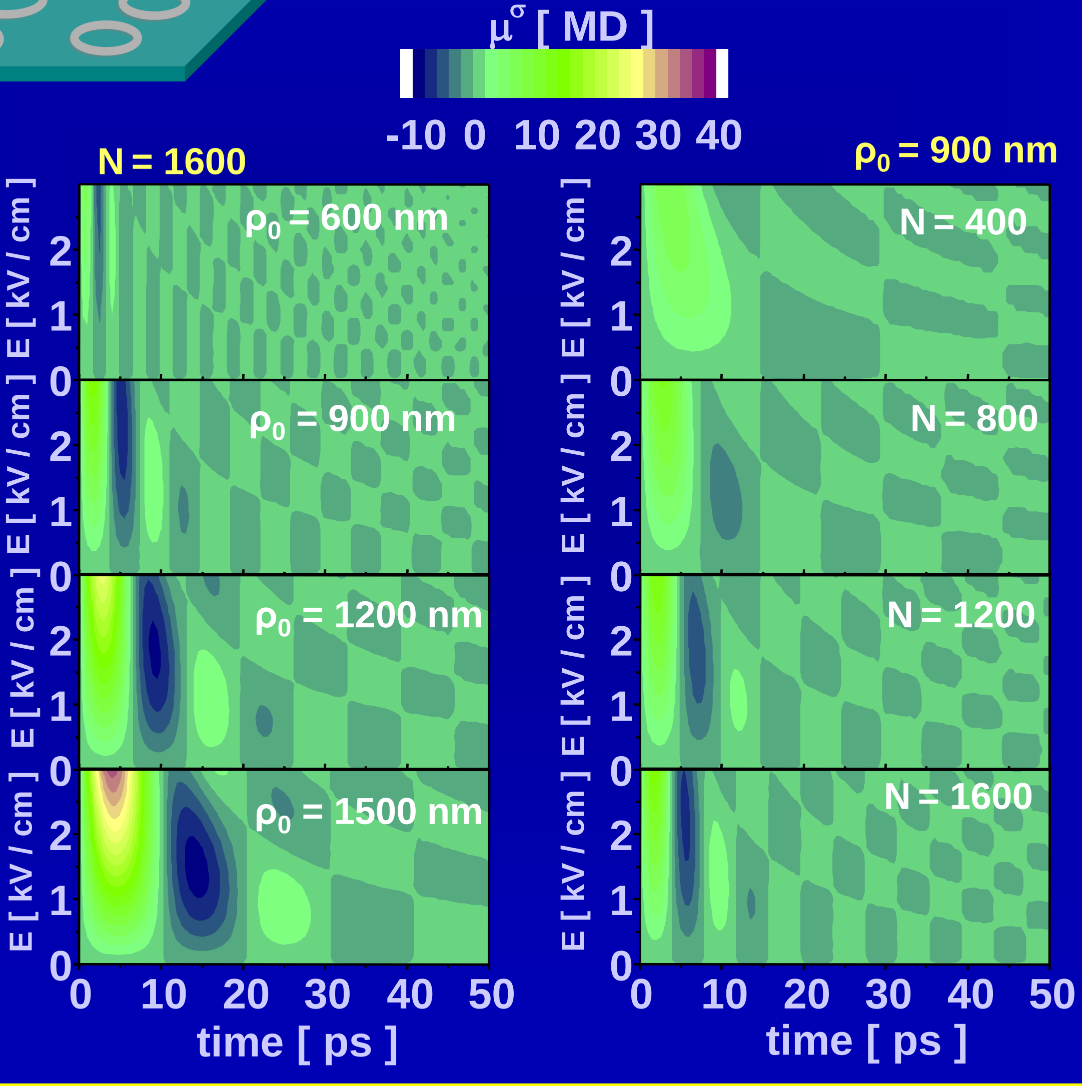
time dependence of the total induced electric **dipole moments** in 10^6 D.
E is the peak-field amplitude. Pulse duration is 1 ps.



dynamical electric dipole moment of ring structures



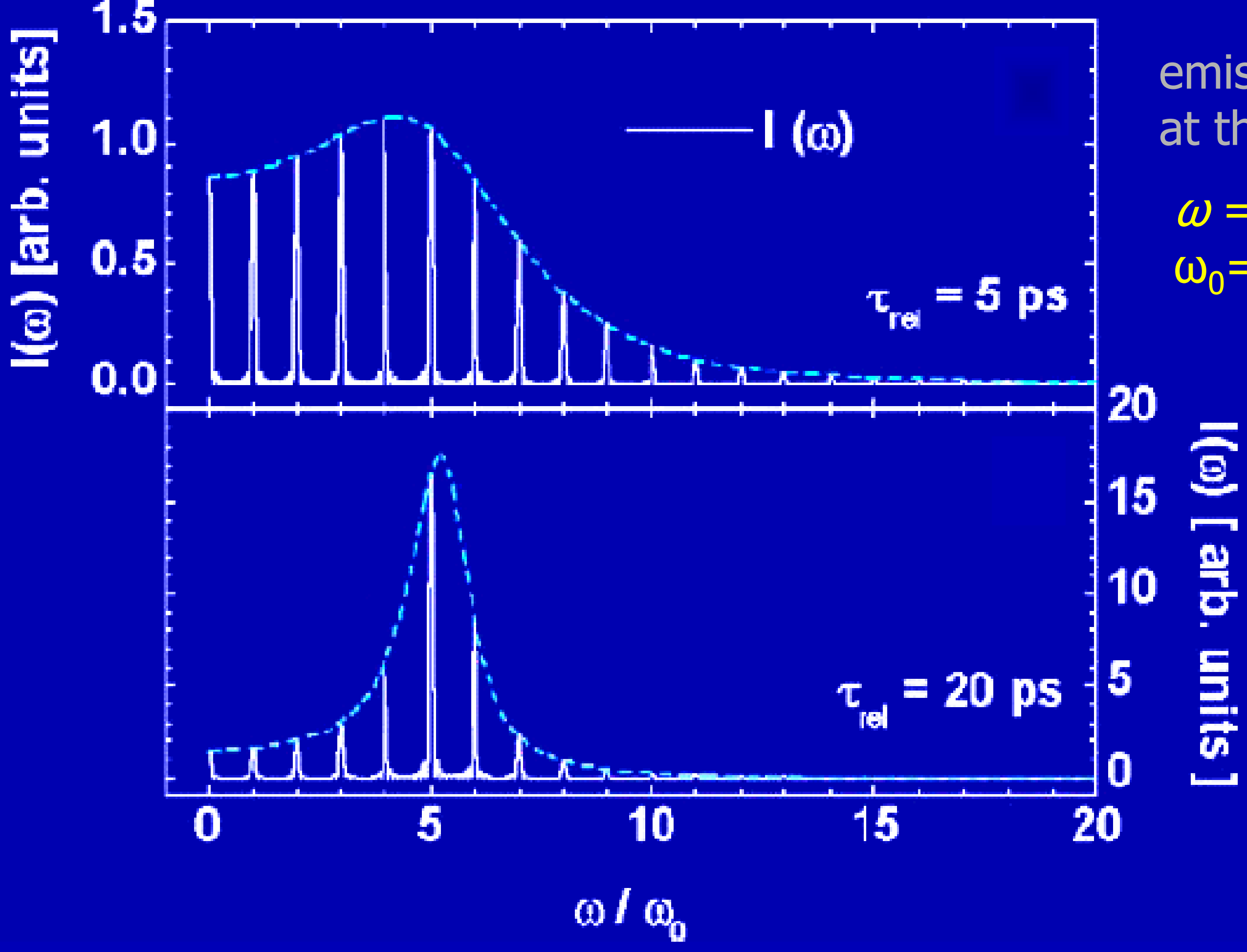




PRL **94**, 166801 (`05)
PRB **77**, 235438 (`08)
PRA 79, 023822 (`09)

ring as light source

$$I(\omega) \sim \left|\mu_k(\omega)\right|^2$$



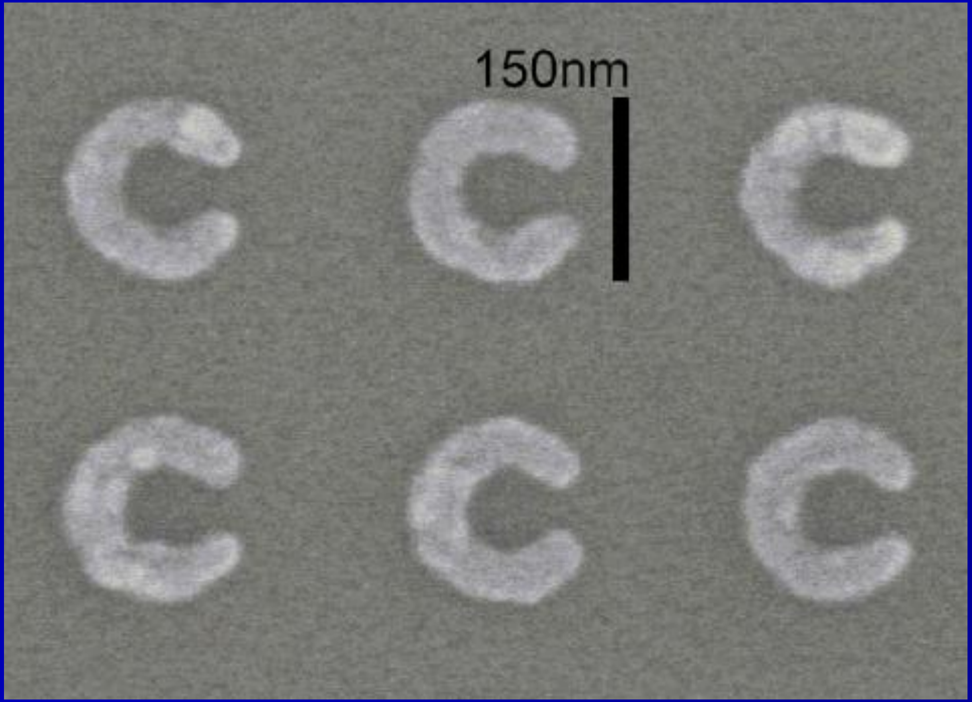
emission spectrum has maxima at the harmonics

$\omega = n\omega_0$, $\omega_0 = 2\pi/T$, n=0,1,2,…
$\omega_0 = 6.3\ 10^{10}$ Hz

train of 10 pulses with 100 ps period.
field amplitude is 1 V/cm. $\omega_0 = 2\pi/T = 6.3\ 10^{10}$Hz

EPL **78**, 57001 (`07); PRB **77**, 235438 (`08)

ring as light source



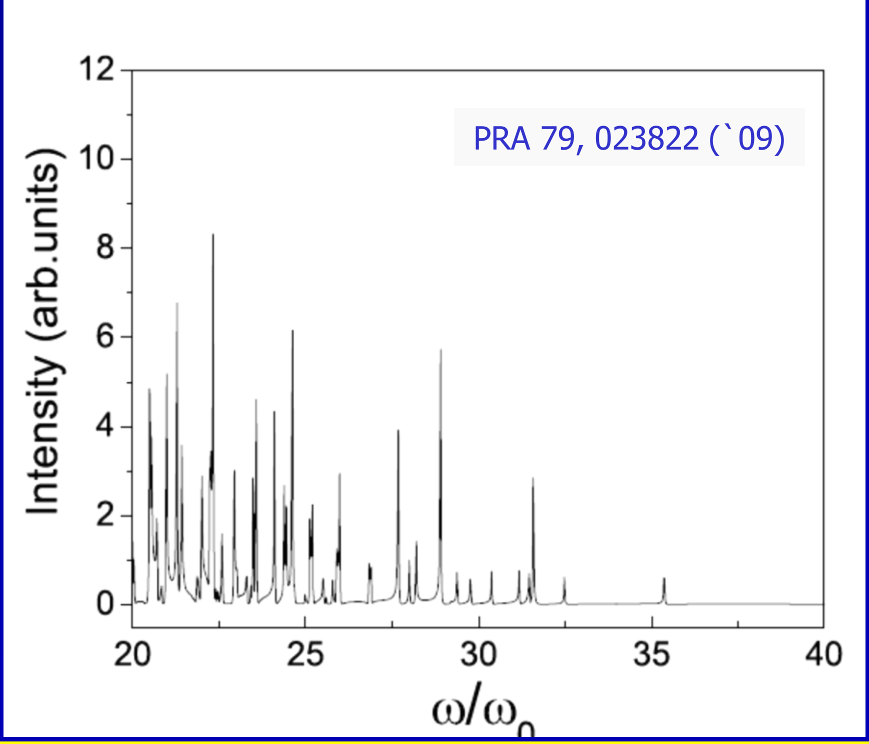
Clark *et al.* APL **93**, 023121 (2008)

$$\tau_d = 1\,ps$$

$$E = 1kVcm^{-1}$$

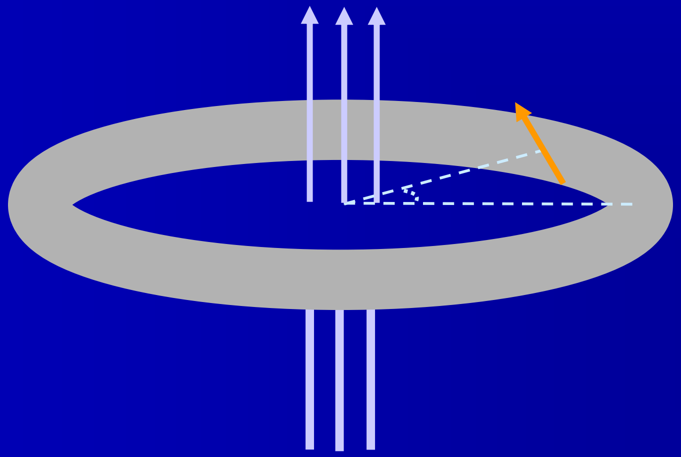
$$V_0 = 10\,meV$$

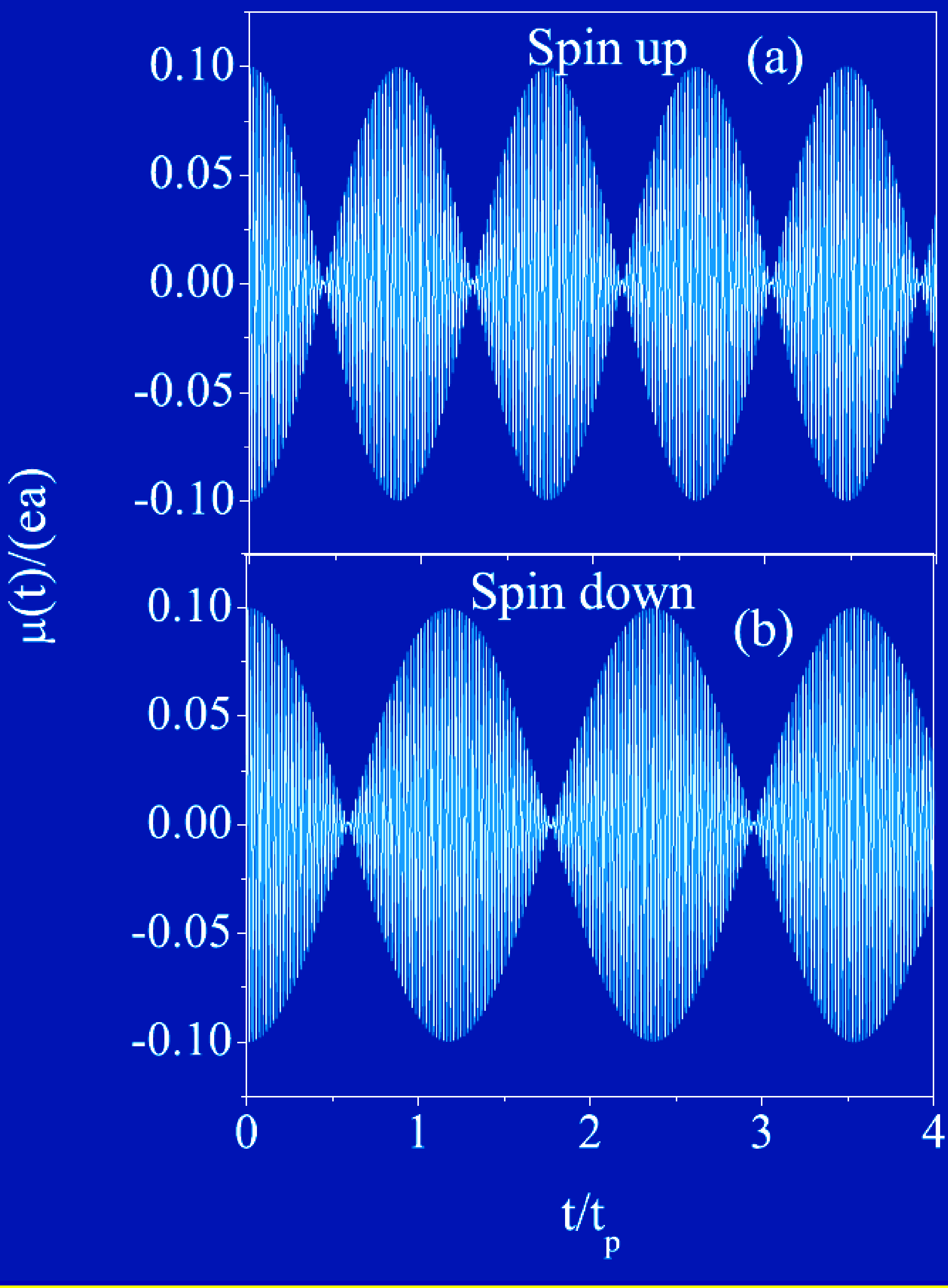
$$\omega_0 \approx 0.1THz$$



PRA 79, 023822 (`09)

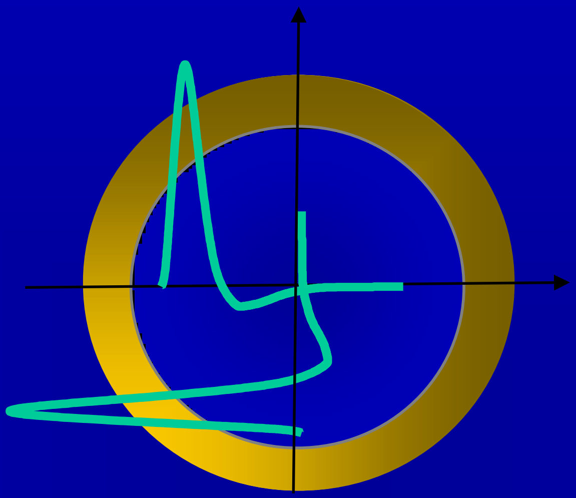
pulse-induced spin dynamics

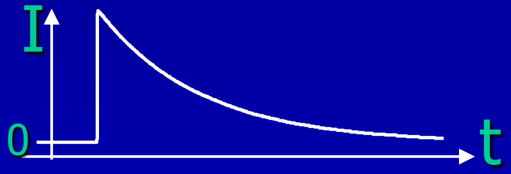




Zhu, Berakdar Phys. Rev. B **77**, 235438 (´08)

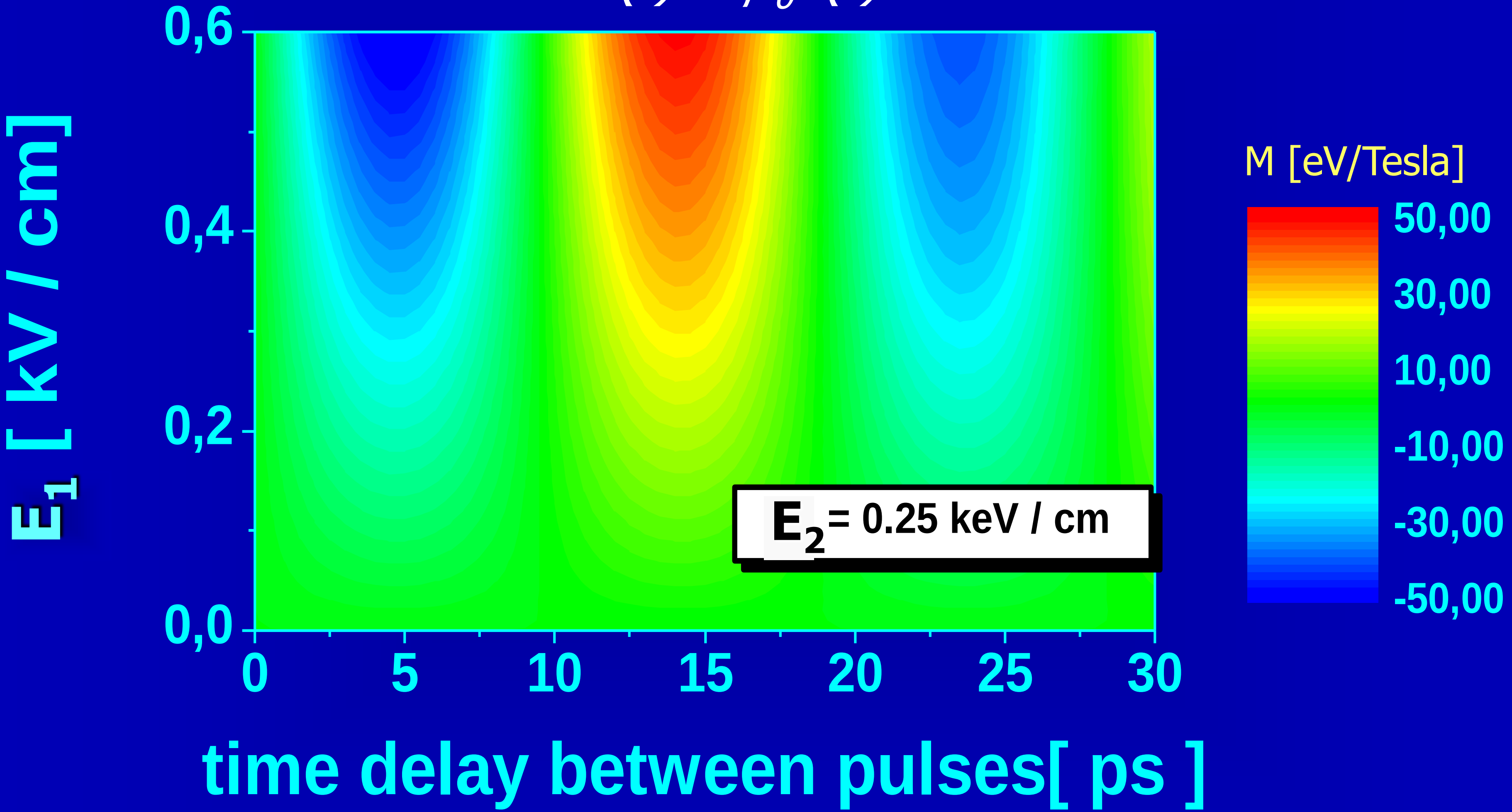
charge current generation





induced magnetization

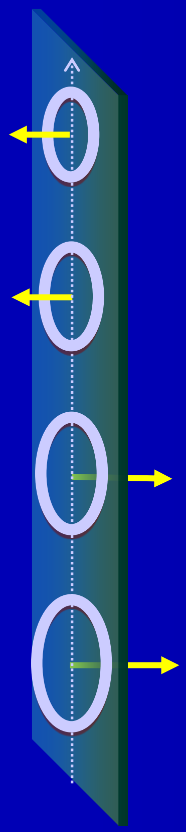
$$M(t)=\pi\rho_0 I(t)$$

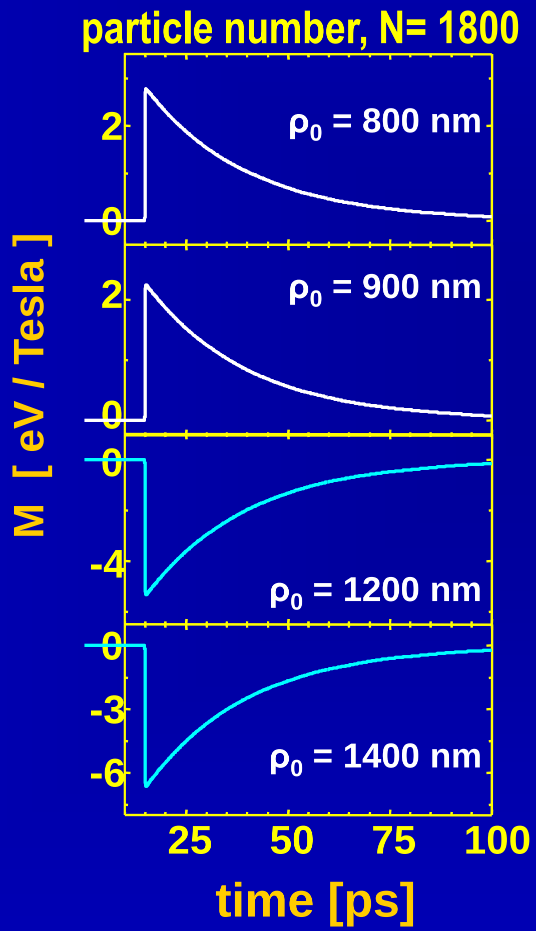


1 Bohr magneton = $e\hbar/2m_e \sim 7 \cdot 10^{-5}$ eV/T

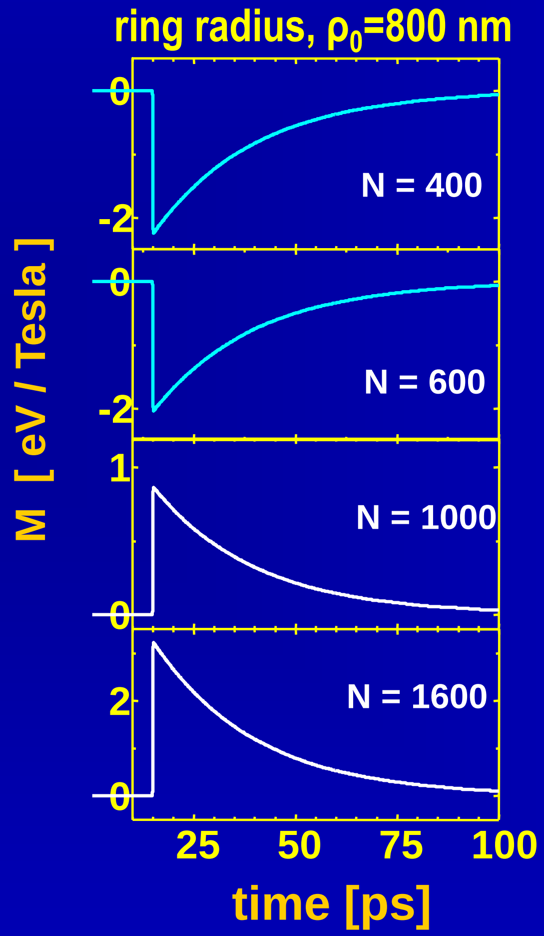
$I = 1\mu A \rightarrow M \sim 112$ eV/Tesla

induced magnetization in ring chains

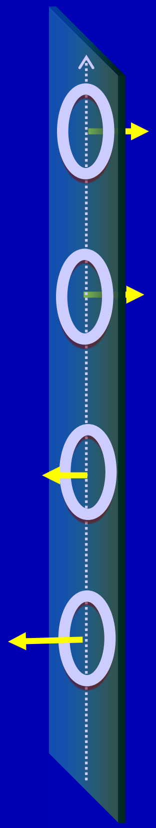




particle number, N= 1800

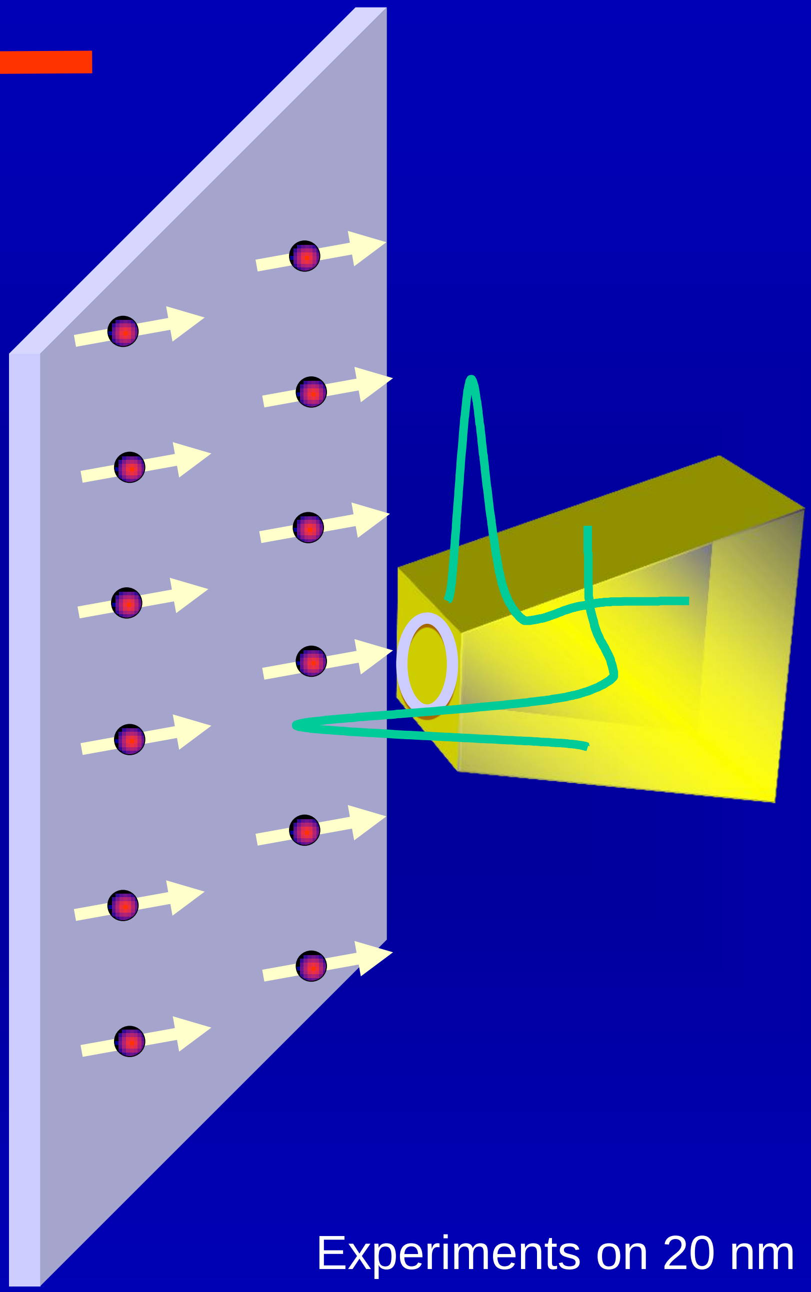


ring radius, ρ_0=800 nm



Matos, Berakdar Phys. Rev. Lett. **94**, 166801 (`05)

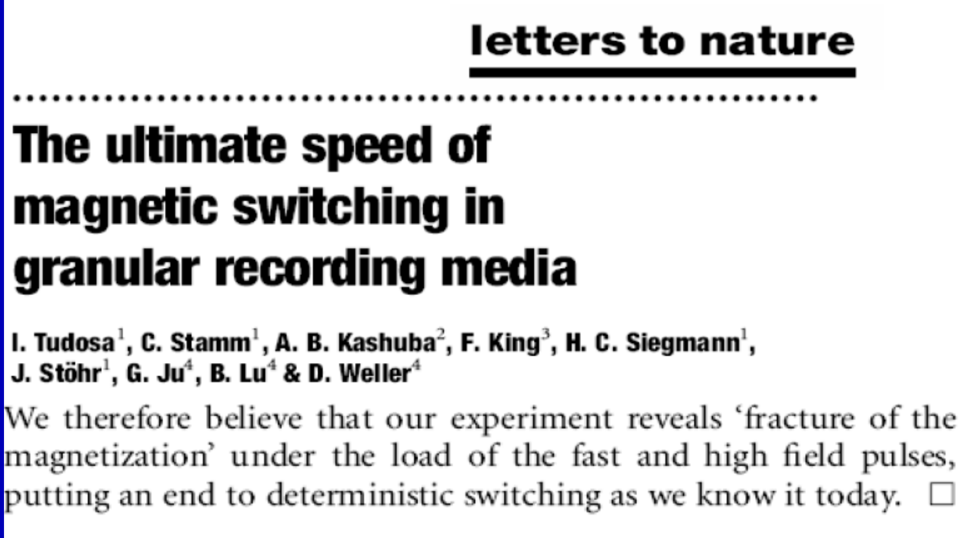
applications…



Experiments on 20 nm **Co** – nanoparticles

C. Thirion *et al.* Nature Mat. **2**, 524 (´03)

applications...

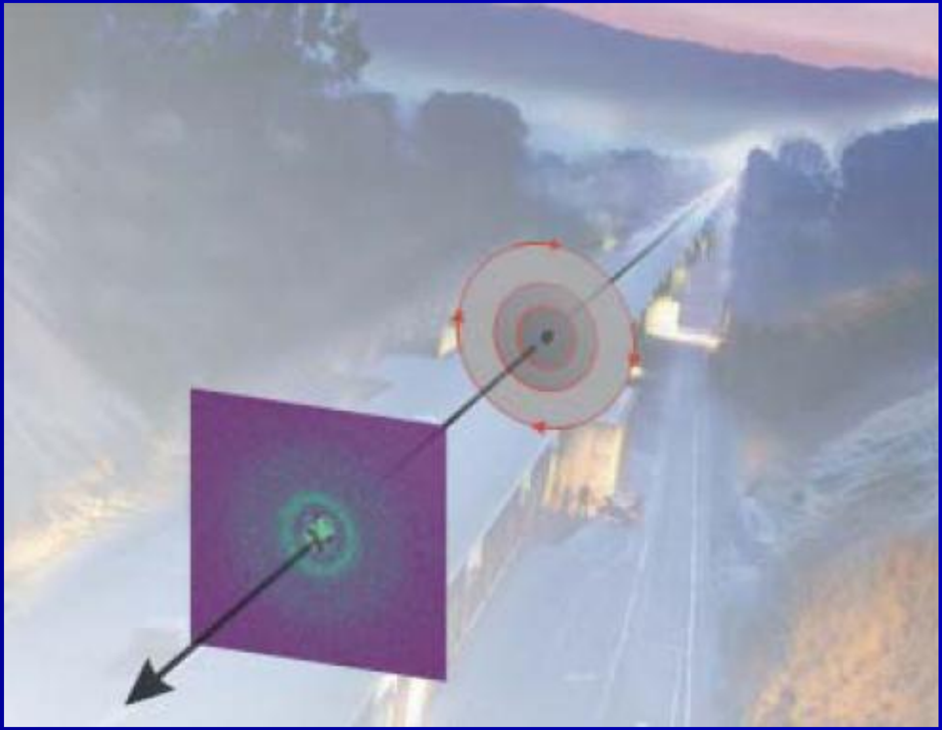


letters to nature

The ultimate speed of magnetic switching in granular recording media

I. Tudosa[1], C. Stamm[1], A. B. Kashuba[2], F. King[3], H. C. Siegmann[1], J. Stöhr[1], G. Ju[4], B. Lu[4] & D. Weller[4]

We therefore believe that our experiment reveals 'fracture of the magnetization' under the load of the fast and high field pulses, putting an end to deterministic switching as we know it today. ☐

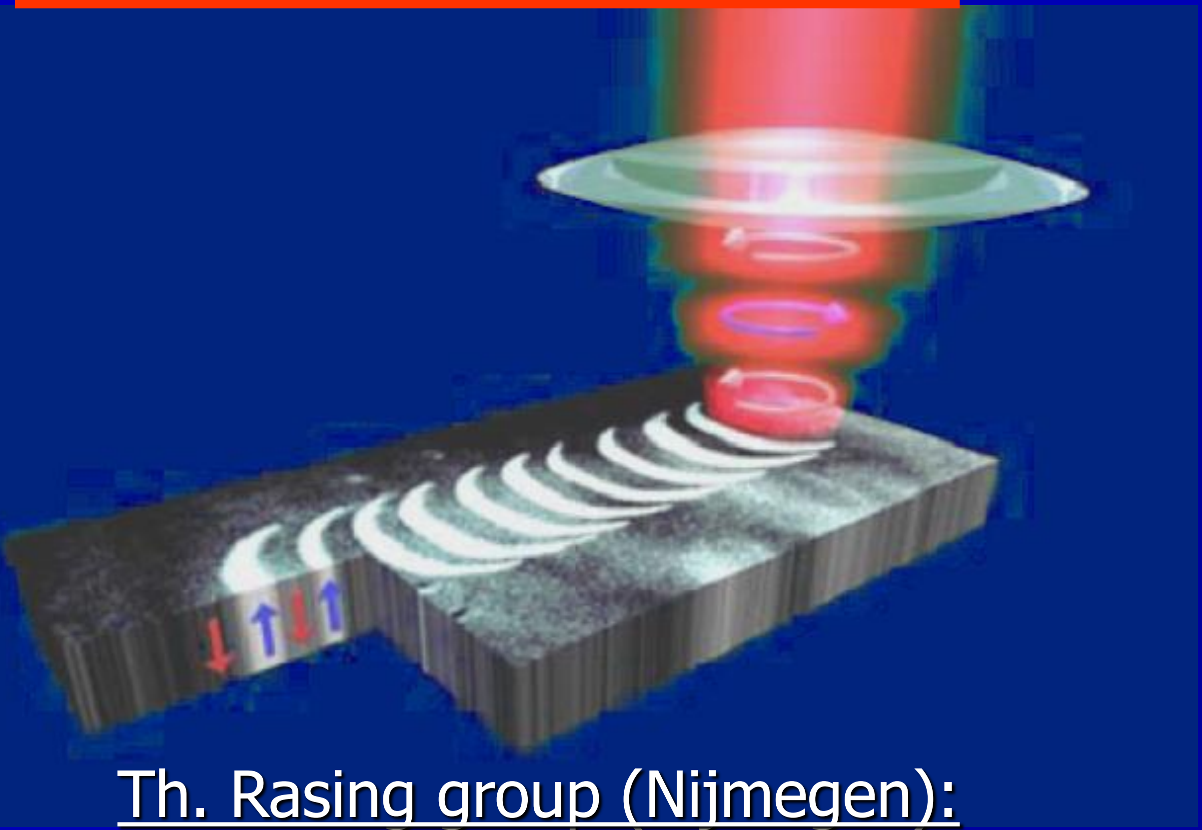


Stanford linear accelerator

τ_d =2.3 ps, several T pulses

Back *et al.*, Phys. Rev. Lett. 81, 3251 (1998)

photo-induced internal magnetic fields



inverse Faraday effect

$$M \propto \chi\left[E \times E^{*}\right]$$

Pitaevskii JETP **12**, 1008 (1961)
van der Ziel PRL **15**, 190 (1965)

Th. Rasing group (Nijmegen):

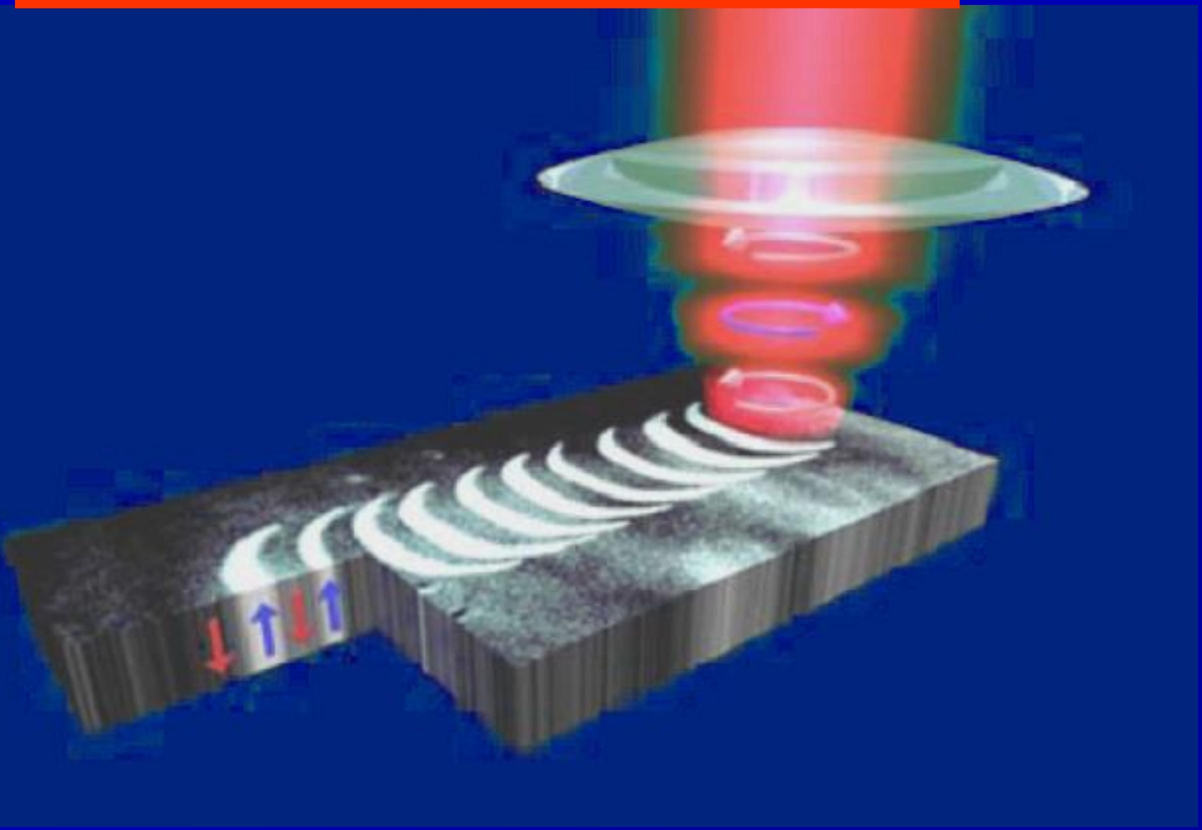
magnetization by instantaneous photomagnetic pulses

Nature **429** 850 (2004)

Nature **435** 655 (2005)

Phys. Rev. Lett. **99**, 047601 (2007)

photo-induced internal magnetic fields



inverse Faraday effect

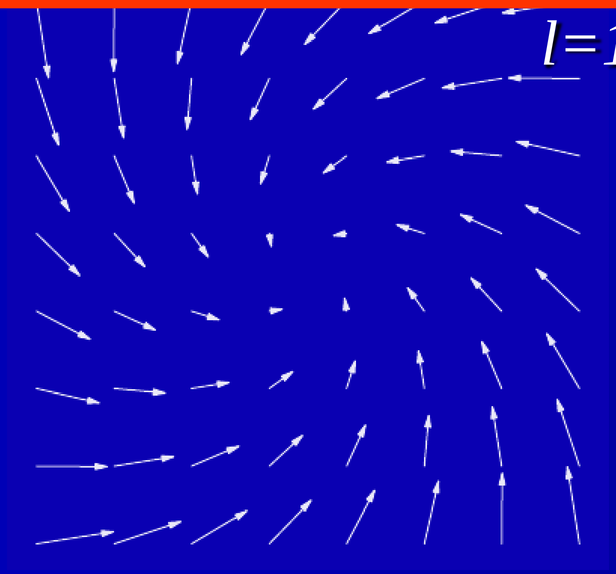
$$M \propto \chi\left[E \times E^{*}\right]$$

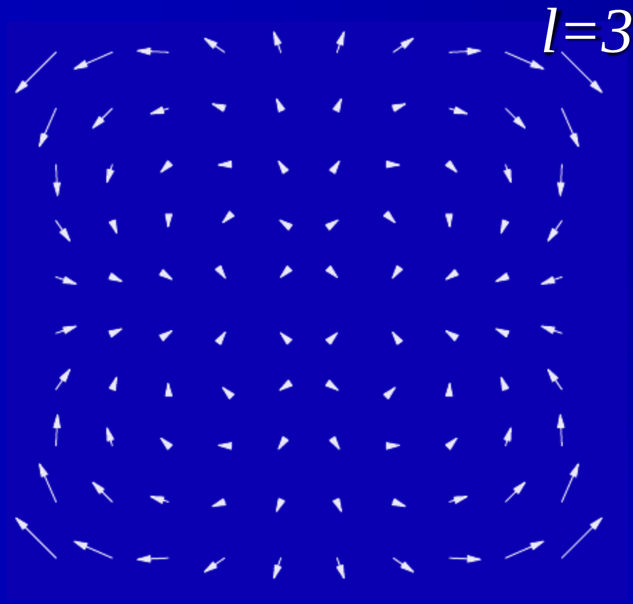
Pitaevskii JETP **12**, 1008 (1961)
van der Ziel PRL **15**, 190 (1965)

Off-resonance, high-frequency strong fields

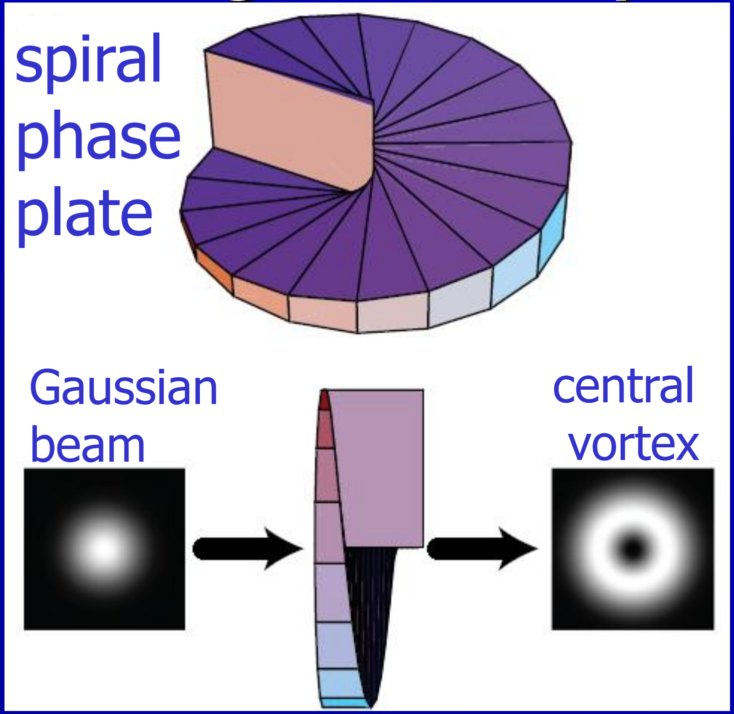
$$\boxed{\mathrm{Re}\langle j(\omega \sim 0)\rangle \propto \frac{i}{2\pi\langle n_0\rangle}\nabla\times\left(\sigma E \times \sigma^{*} E^{*}\right)}$$

photo-induced internal magnetic fields





mag. fields via optical vertices



Allen, Padgett group (Glasgow)

PRA **45**, 8185 (`92)
Opt. Com. **96**, 123 (´93)

Quinteiro, Berakdar, Optics Exp. **17**, 20466 (2009)

summary

1. experimental status
2. photo-induced polarization and charge currents
3. magnetic pulses: generation and control
4. applications
5. future directions