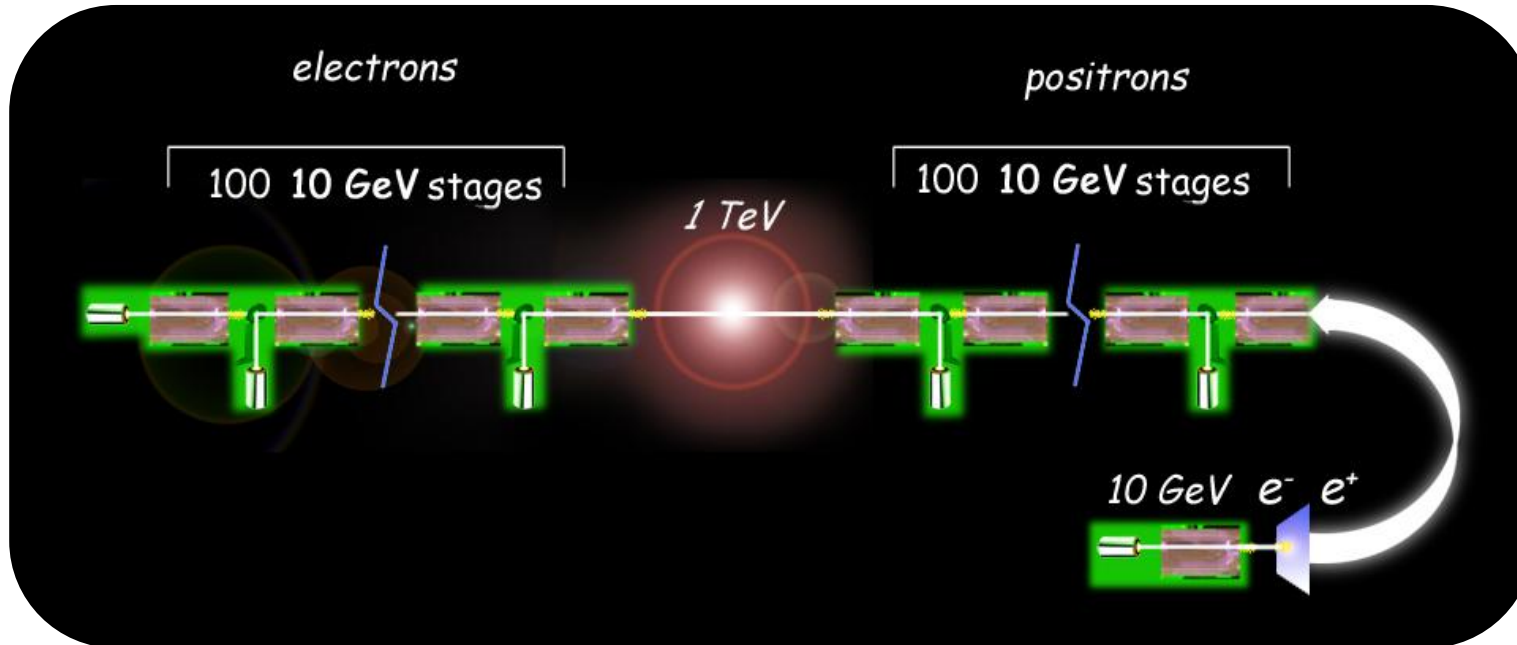# Simulations of electron and positron polarization preservation in plasma

Johannes Thomas[1], Yitong Wu[3], Anna Hützen[1,2], Alexander Pukhov[1], Liangliang Ji[3], and Markus Büscher[1,2]
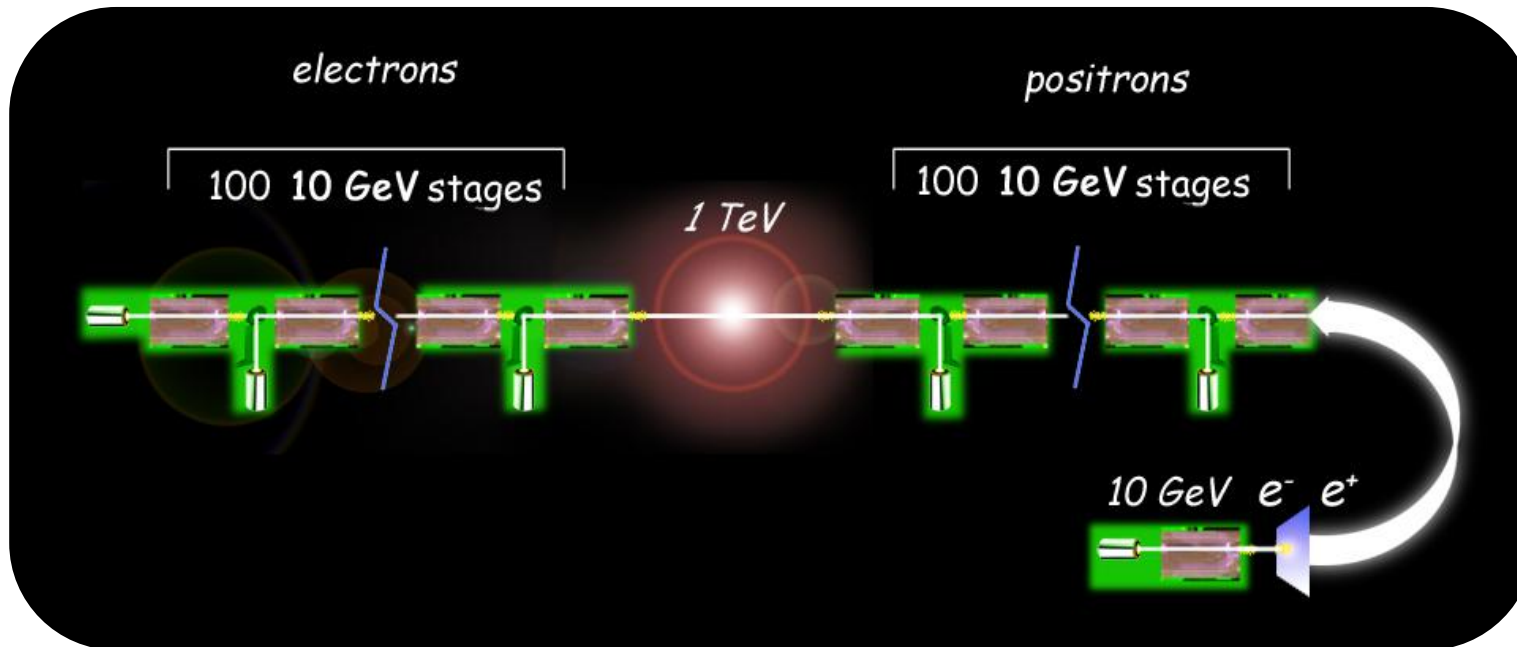
[1]University of Düsseldorf , [2]Forschungszentrum Jülich

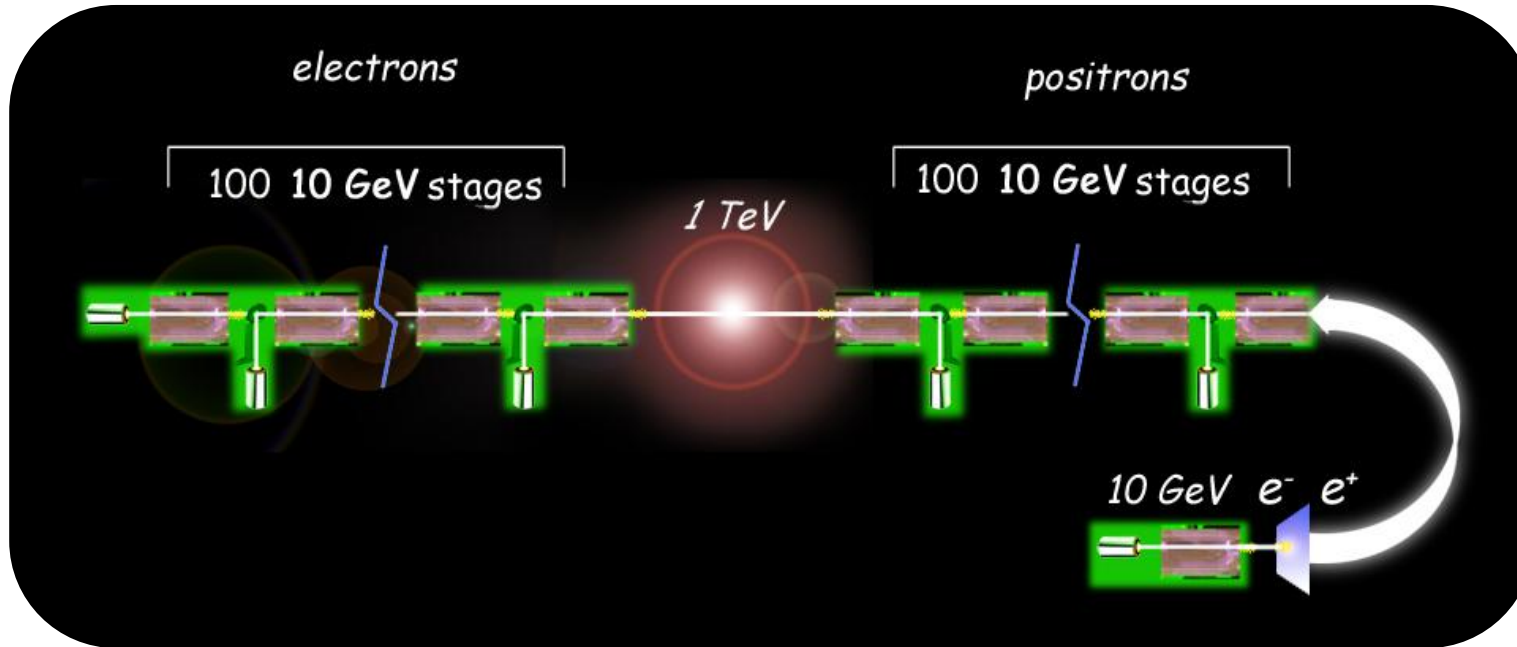[3] SIOM, Chinese Academy of Sciences, CAS - all in Shanghai

Motivation

If you work on particle acceleration in plasma you think about:

- energy (maximum, spread)
- emittance (4D and 6D)
- beam charge and current
- repetition rate

- beam quality and luminosity
- plasma density
- transformer ratio
- staging, coupling, injection

Motivation

A collider running with polarized beams has certain advantages because:

- Certain observables with high sensistivity to the electroweak parameters can be measured directly only with polarized beams.

- Precise measurement of the top quark electroweak couplings and couplings associated with Higgs boson decays would be exessible.

Brigitte Cros et al., arXiv:1901.10370v2 (2018); Paul Preuss, LBNL, Accelerators and Light Sources of Tomorrow (2009)

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The Problem

The Source

The Coupling

The Acceleration

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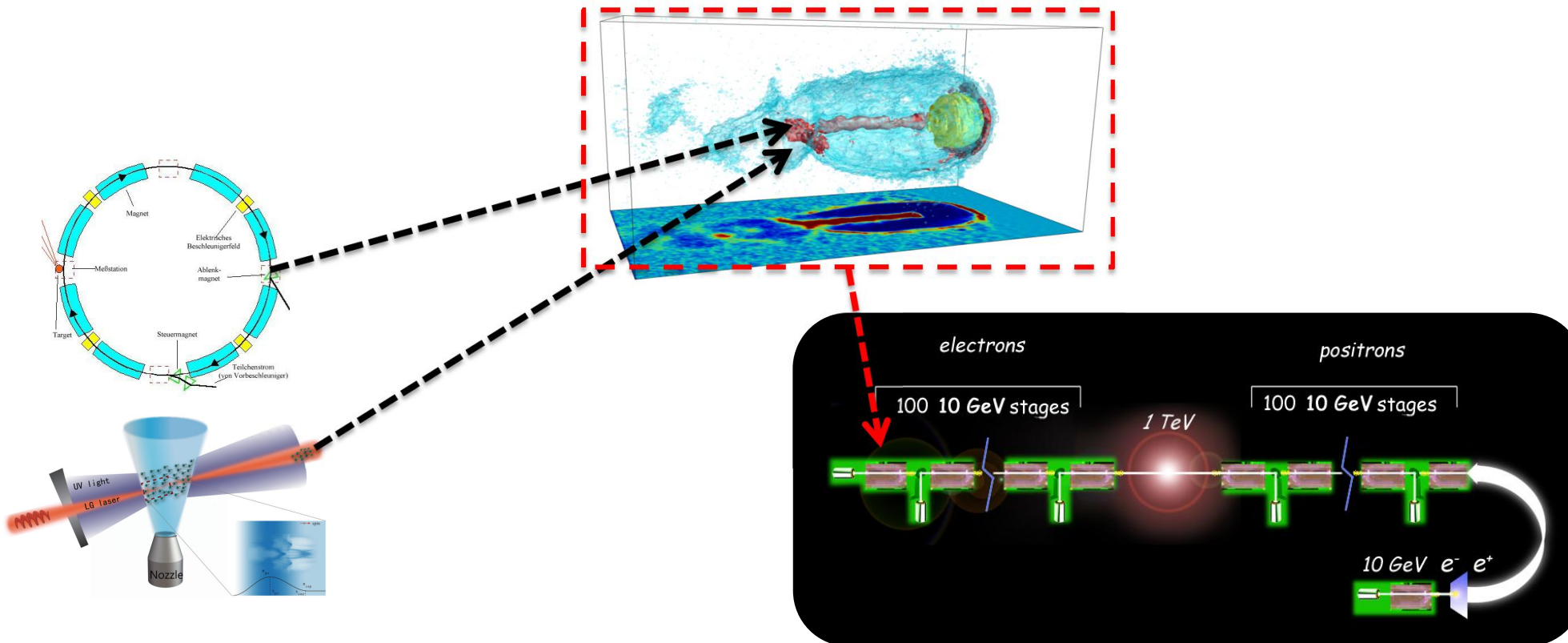
The Problem

SOURCE

- gas target where the electron spins are already aligned before laser irradiation
- pre-accelerated and pre-ionized bunches

COUPLING

- polarization losses and emittance growth must be minimized
- bunch charge must be maximized

ACCELERATION

- depolarization must be prevented / minimized
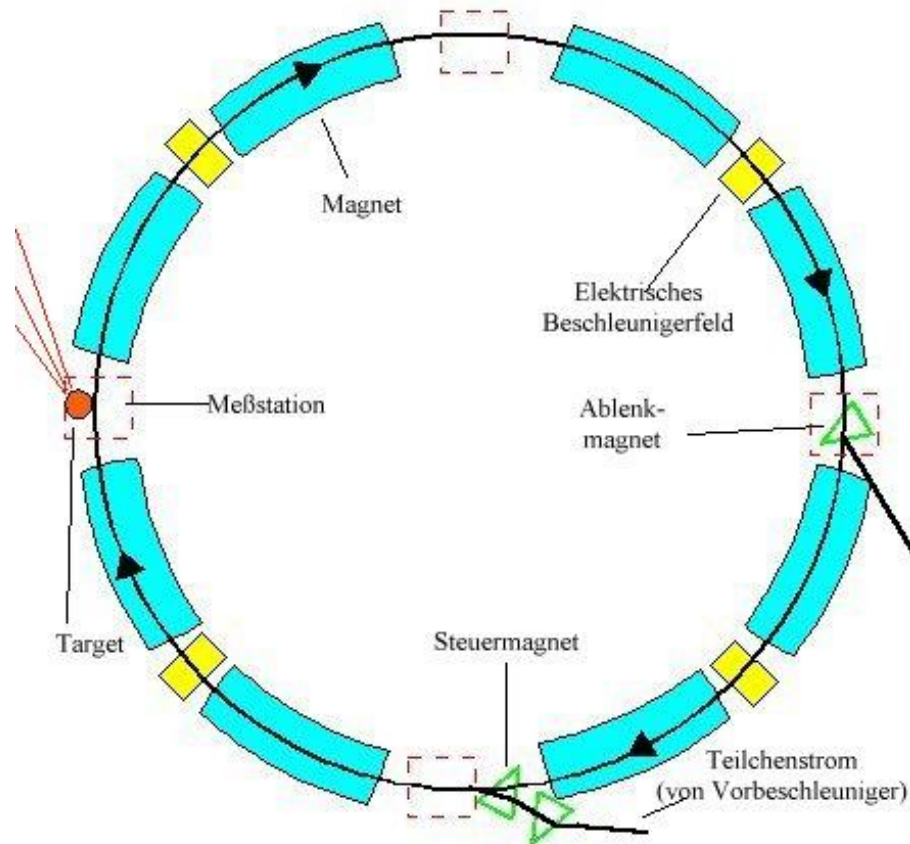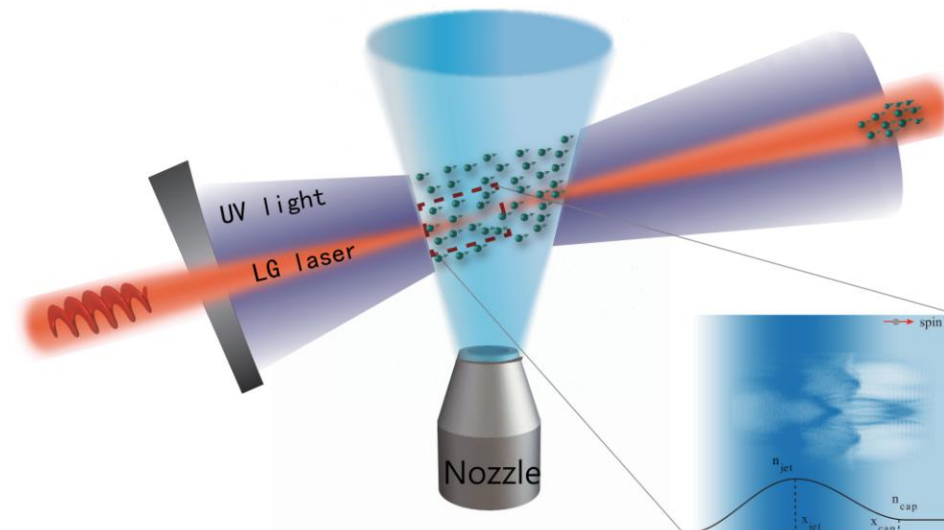- spontaneous polarization build-up is not expected

The Source

1st option
Wait until electron and positron beams are polarized in a storage ring.

2nd option
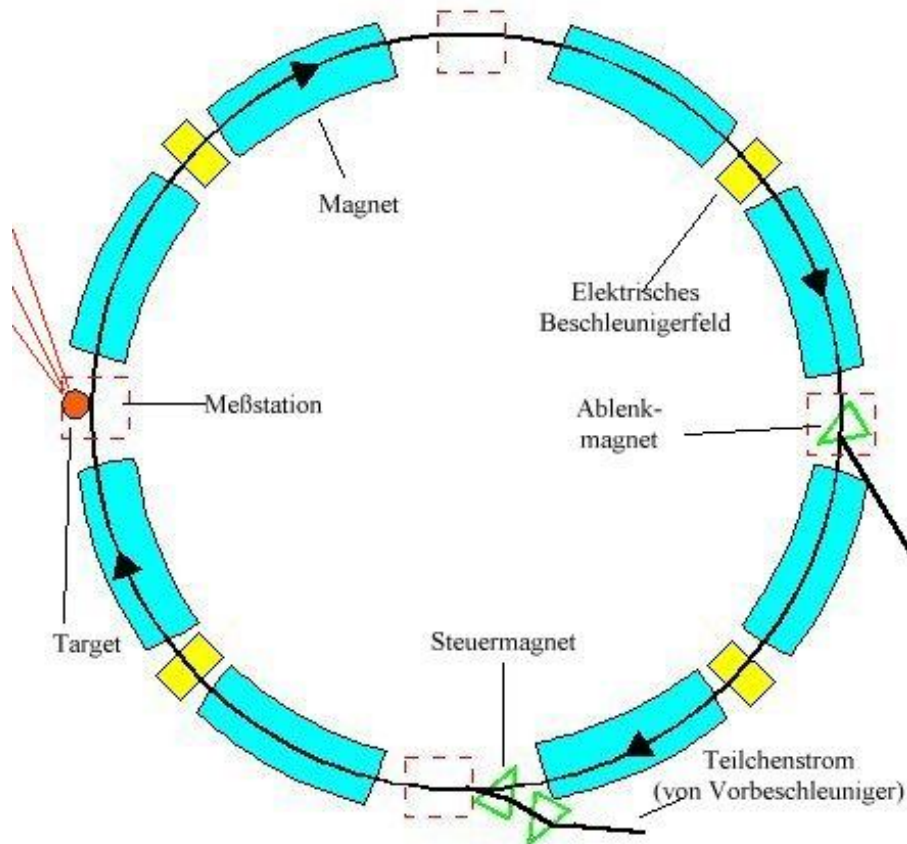Spin-polarized particle beams from laser-plasma accelerators

The 1st Source

1st option

Wait until electron and positron beams are polarized in a storage ring.

- achievable polarization: up to 92%

- energy in the GeV range

- polarization time for electrons in the range of minutes to hours

- storage-ring length in the km range

The 2nd Source

2nd option
Spin-polarized particle beams
from laser-plasma accelerators

Sketch of the all-optical laser-driven polarized electron acceleration scheme:

- UV light (213 nm) to photo-dissociate HCl molecules
- a 1064 nm IR laser aligns the bonds of the HCl molecules,
- a 234.62 nm UV laser ionizes the Cl atoms
- an electric field removes the Cl atoms from the target volume
- a coaxial LG laser pulse traverses the H gas target to accelerate the polarized electrons via wakefield acceleration
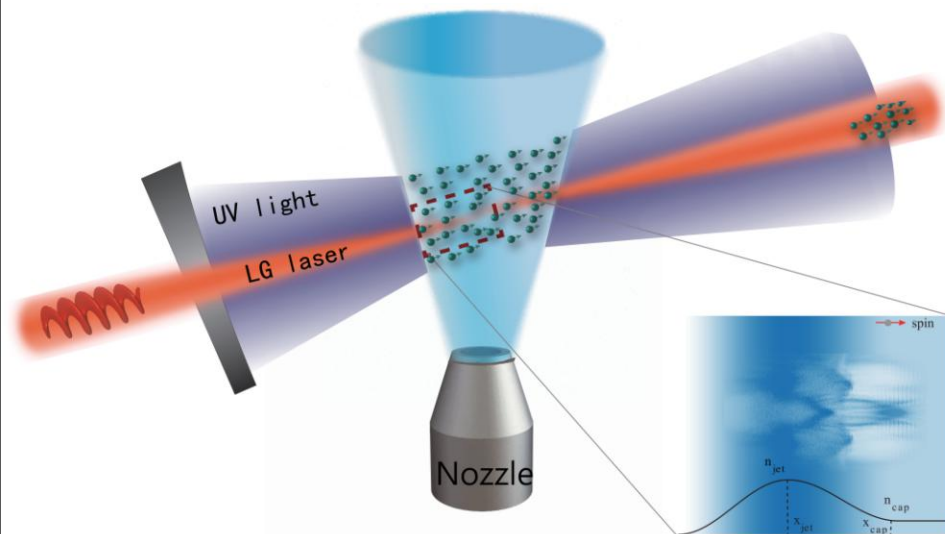
2nd option
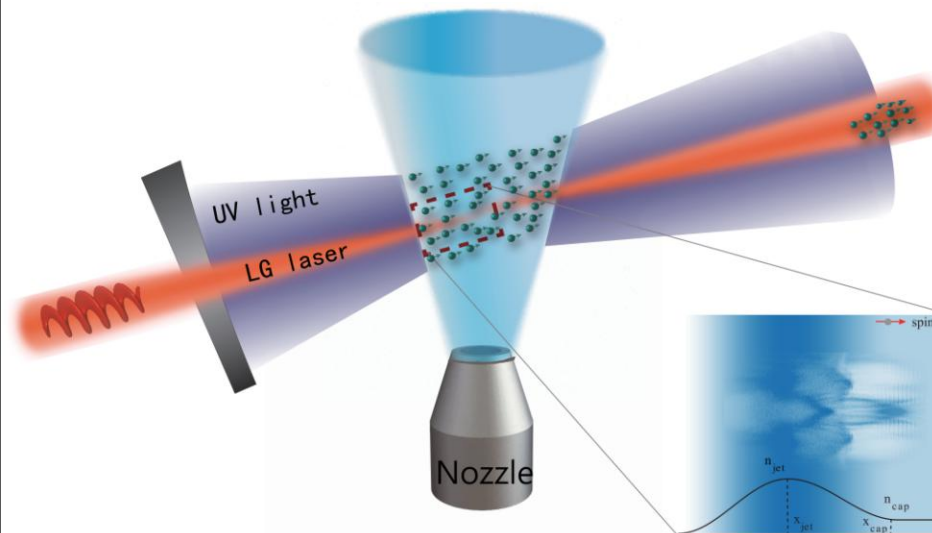Spin-polarized particle beams
from laser-plasma accelerators

evolve according to the T-BMT equation

$$\frac{d\mathbf{s}}{dt} = -\vec{\Omega} \times \mathbf{s}.$$

In cgs units the rotation frequency is simply [10]

$$\vec{\Omega} = \frac{q}{mc}\left[\Omega_B\mathbf{B} - \Omega_v\left(\frac{\mathbf{v}}{c}\cdot\mathbf{B}\right)\frac{\mathbf{v}}{c} - \Omega_E\frac{\mathbf{v}}{c}\times\mathbf{E}\right],$$

where

$$\Omega_B = a + \frac{1}{\gamma}, \quad \Omega_v = \frac{a\gamma}{\gamma+1}, \quad \Omega_E = a + \frac{1}{1+\gamma}.$$

Y. Wu et al, submitted to nat. com.; S. R. Mane, Y. M. Shatunov and K. Yokoya, Reports on Progress in Physics 68, 1997-2265 (2005).
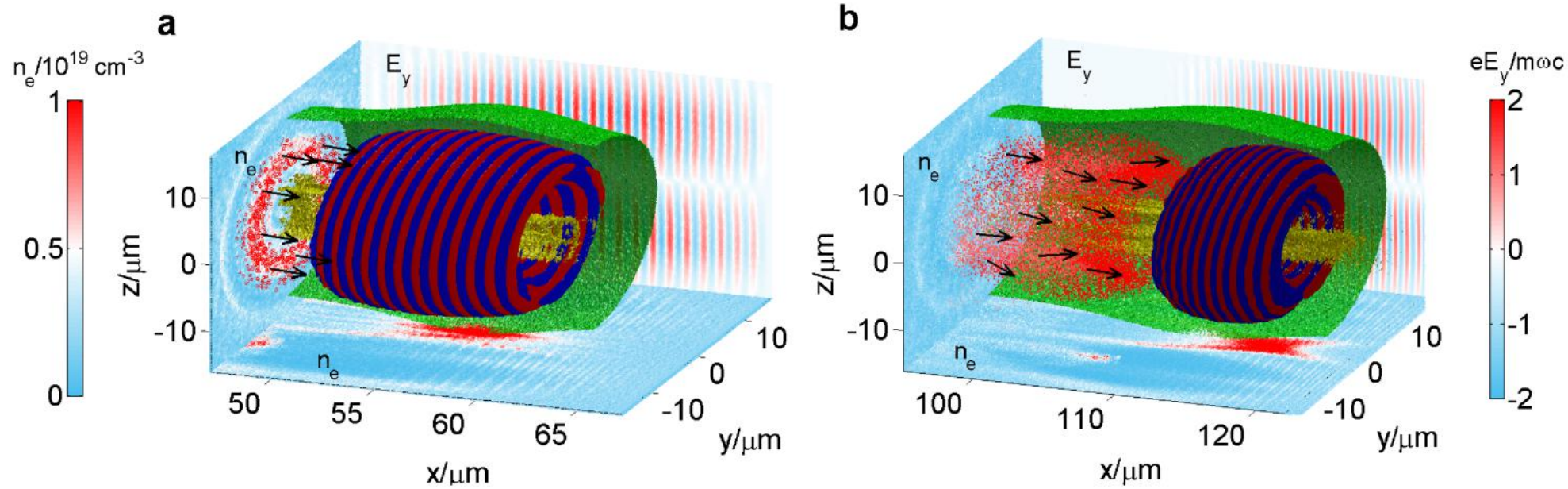
The 2nd Source

The Problem

The Source

The Coupling

The
Acceleration

Summary

- coaxial LG with unique transverse intensity profile
- different topology introduced to the wakefield/bubble structure
- electrons clusterize off axis in the donut-shaped bubble
- electrons get injected as a ring bunch

The 2nd Source
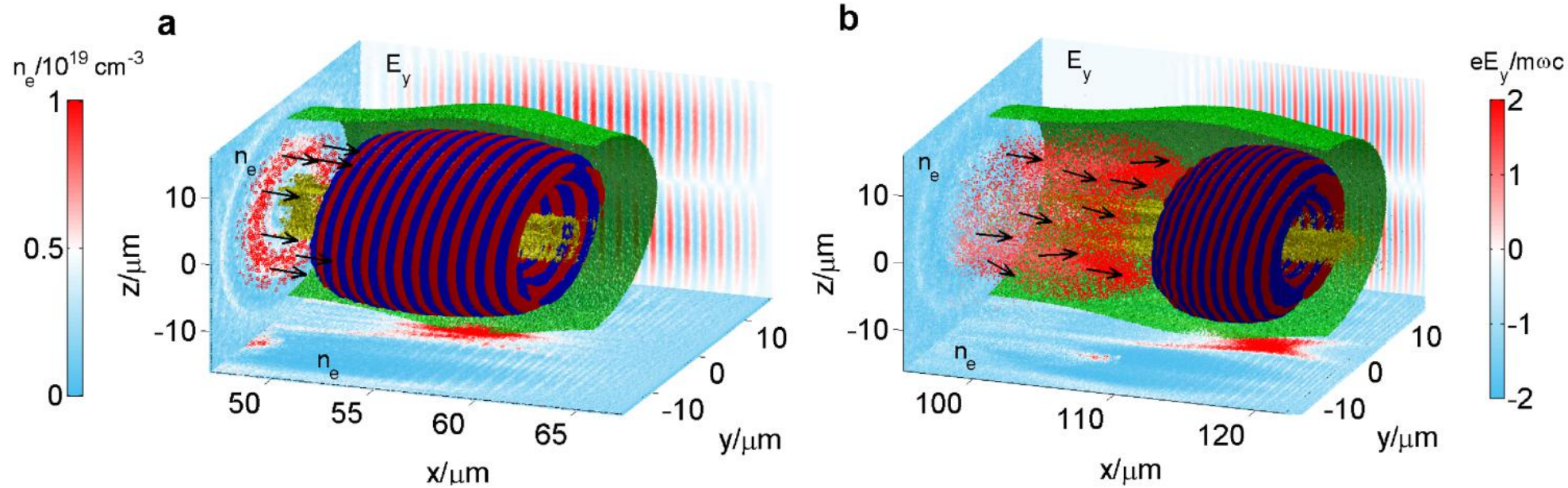
- electrons near the symmetry axis leak through the beam center and form a counter-propagating return flux
- the B field is compensated by the anti-clockwise field generated by the return current
- the B field is lowered down but the total beam charge is maintained
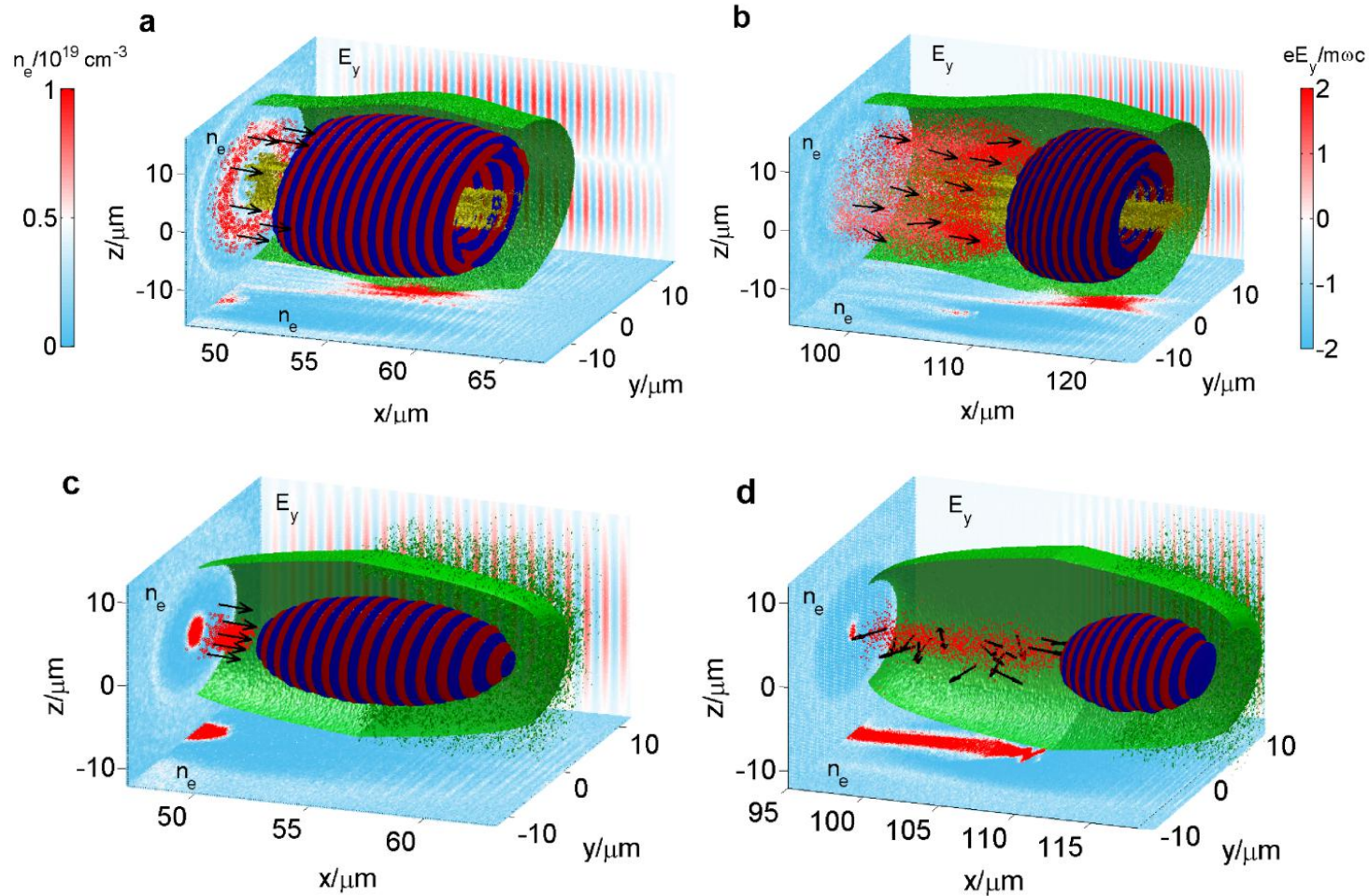- electrons are accelerated to 5 MeV

Wu et al, submitted to nat. com.

- coaxial LG beam maintaince polarization (>80%)
- in Gaussian beam polarization is lost almost immediately

The Problem

The Source

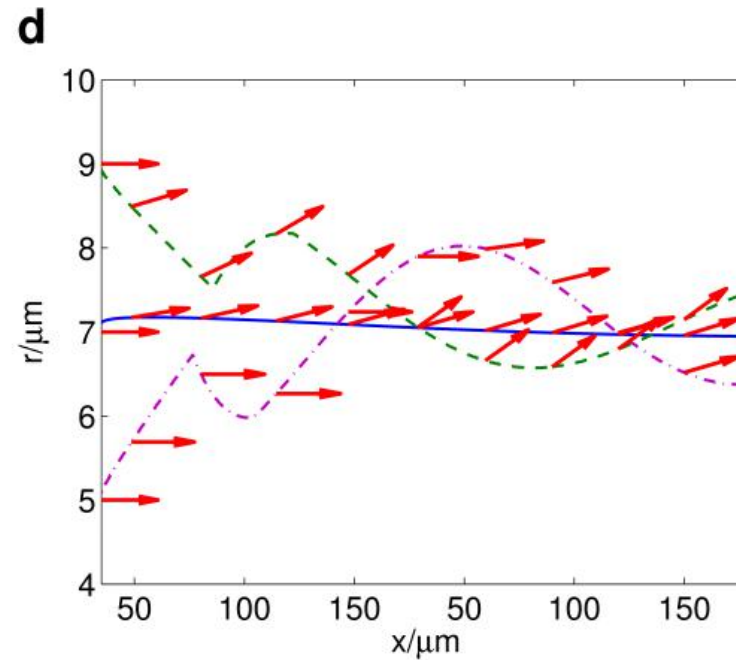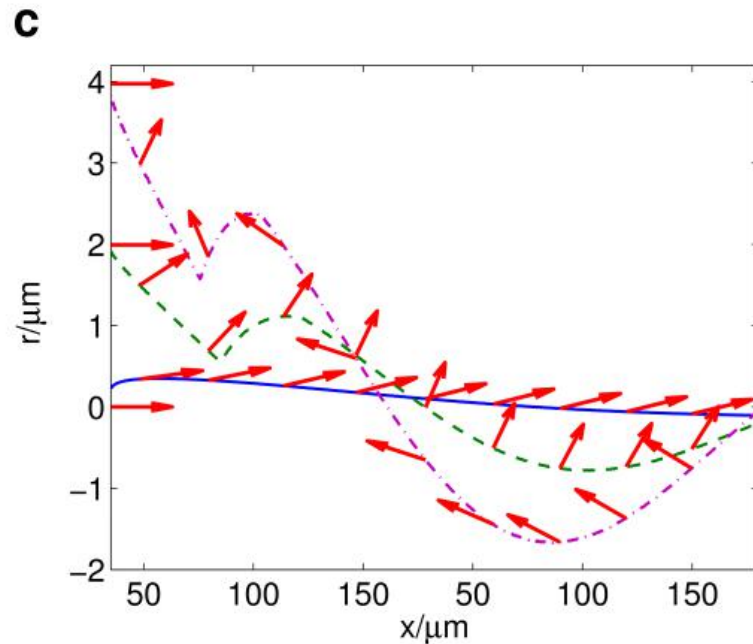The Coupling

The Acceleration

Summary

The 2nd Source

LEFT: in the Gaussian case, the electron spins oscillate incoherently at high frequencies and lose their initial spin orientations instantly

RIGHT: the spin precession time in the LG case is large compared to the acceleration duration
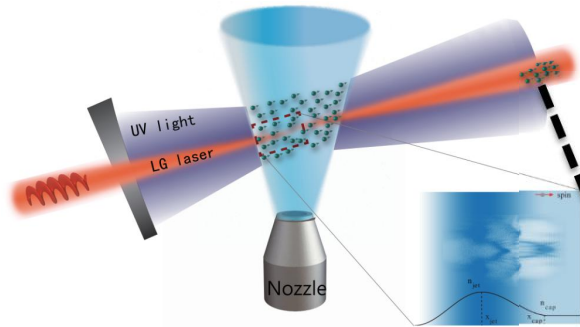
The Problem

The Source

The Coupling

The Acceleration

Summary

The Coupling

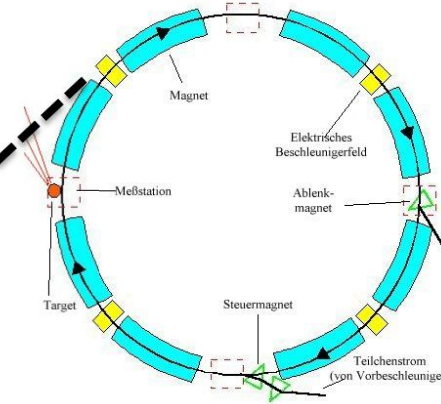- staging at the MeV level
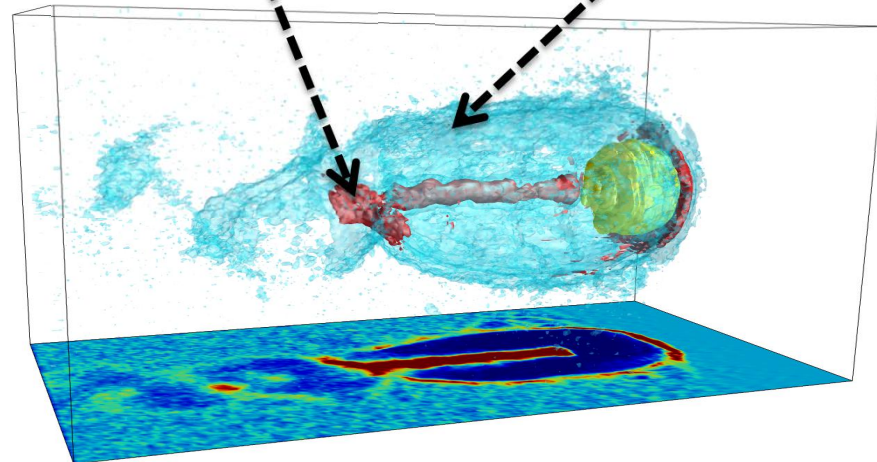
- lateral injection
- on axis

Possible (De-)Polarization mechanisms

- **(asynchrone) spin rotation described by the T-BMT equation**
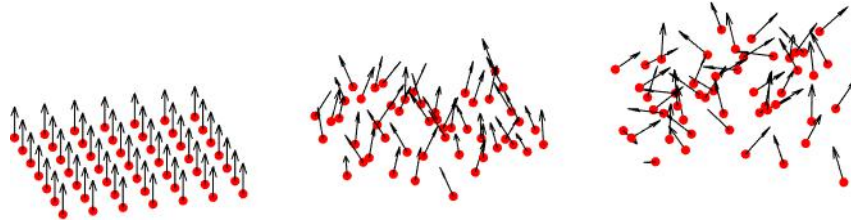
- **beam splitter (Stern-Gerlach)**
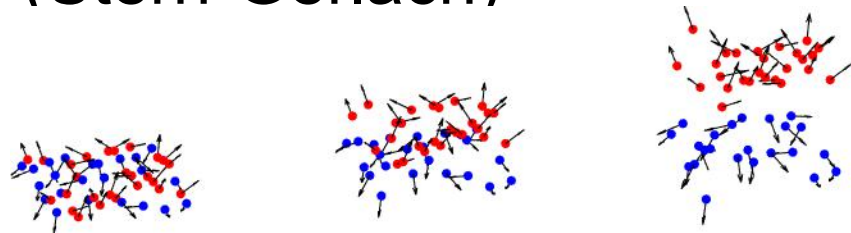
- **self-polarization (Sokolov-Ternov)**
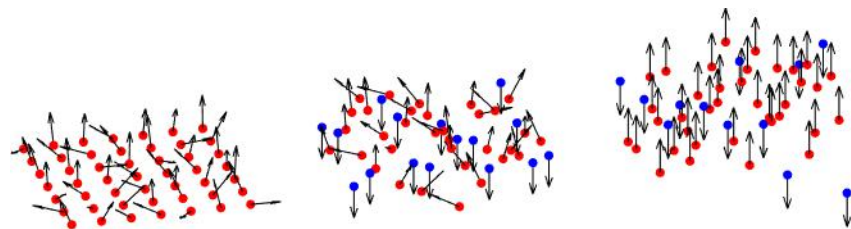
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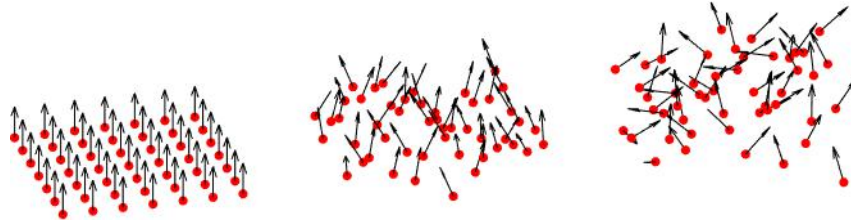
implemented in PIC, fluid and quasi-static codes

- **beam splitter (Stern-Gerlach)**

always discussed away:
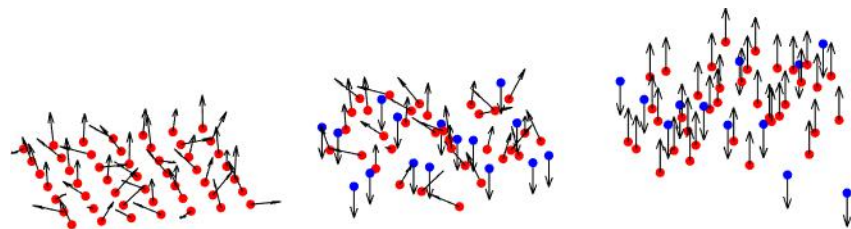
- SGT is weaker than Lorenz force

- **self-polarization (Sokolov-Ternov)**

- ST is coupled to radiation which is neglegible

evolve according to the T-BMT equation

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where

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- If an electron bunch has zero emittance, all particle spin vectors precess coherently.

- If all spins are synchronised, the beam polarization changes its orientation but its norm is conserved.

- How long can a given polarization be conserved, if the spins stay synchronized?

- How long can a given polarization be conserved, if the spins precess incoherently?

The Problem

The Source

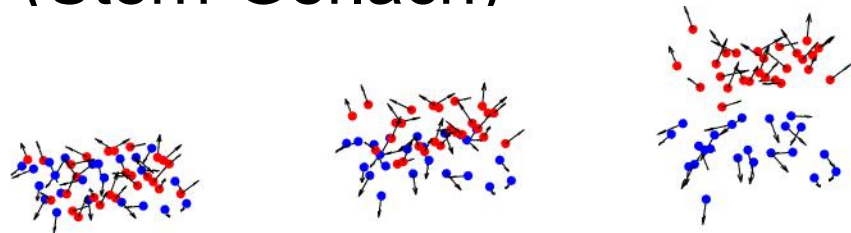The Coupling

The Acceleration

Summary

Depolarization due to asynchron spin rotation
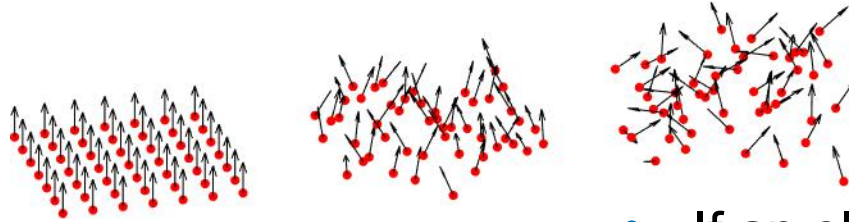
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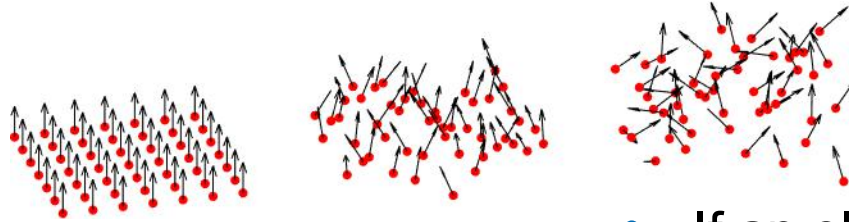
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Depolarization due to asynchron spin rotation

The Problem

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The Coupling

The Acceleration

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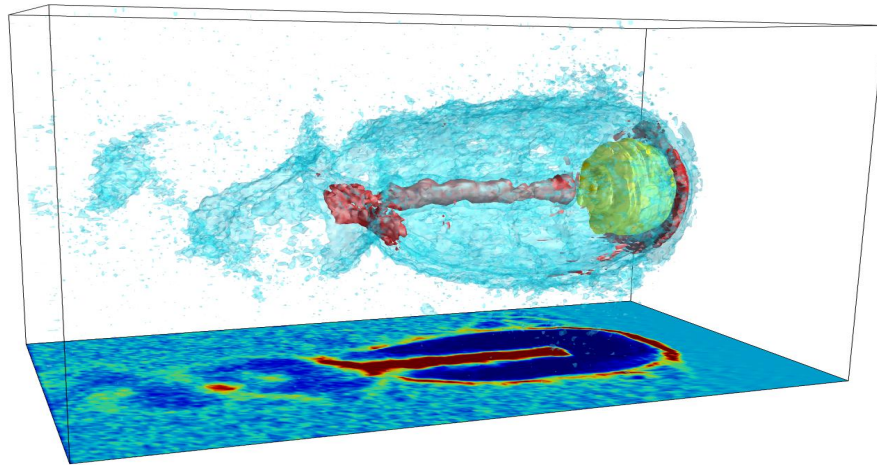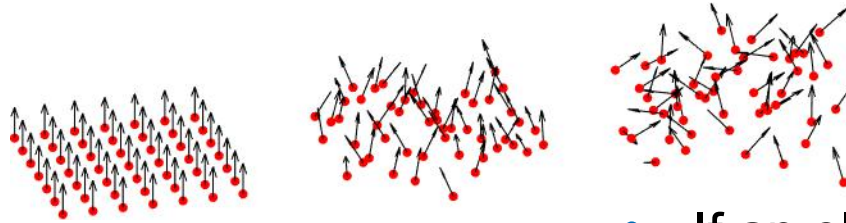- How long can a given polarization be conserved, if the spins precess incoherently?

- inside the laser
- in front of the laser
- in the wake
- in the sheath
- in the bunch

Depolarization due to asynchron spin rotation

$$T_{D,e} \propto \frac{\pi}{2\Omega_{e,GeV}} = \frac{\pi}{6a_e F}$$

- this formula holds for arbitrary field strength
- no information about field configuration
- this formula is to harsh
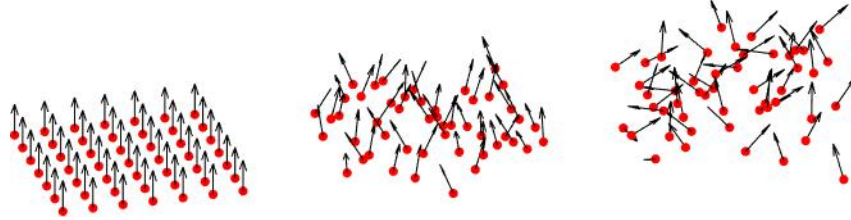- better estimations possible if fields are known

The Problem

The Source

The Coupling

The Acceleration

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Depolarization due to asynchron spin rotation
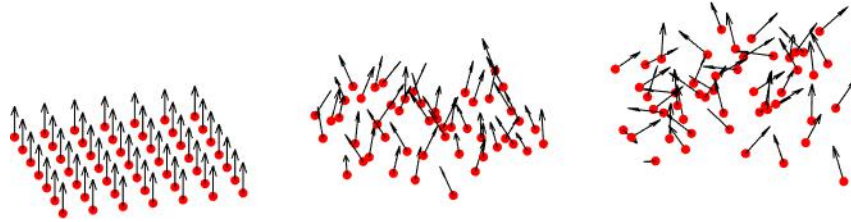
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- ■ better estimations possible if fields are known

$$\mathbf{E} = E_r \mathbf{e}_r + E_z \mathbf{e}_z$$

$$\mathbf{B} = B_\phi \mathbf{e}_\phi$$

$$\frac{ds_r}{dt} = s_z \left(a + \frac{1}{\gamma} \right) F_r + s_\phi \dot{\phi}$$

$$\frac{ds_z}{dt} = -\left(a + \frac{1}{\gamma} \right) F_r s_r$$

$$\frac{ds_\phi}{dt} = -s_r \dot{\phi},$$

The Problem

The Source

The Coupling

The Acceleration

Summary

Depolarization due to asynchron spin rotation

The Problem

The Source

The Coupling

The
Acceleration

Summary

sumilation of single particle spin

$$\mathbf{E} = E_r \mathbf{e}_r + E_z \mathbf{e}_z$$

$$\mathbf{B} = B_\phi \mathbf{e}_\phi$$

$$\frac{ds_r}{dt} = s_z \left(a + \frac{1}{\gamma} \right) F_r + s_\phi \dot{\phi}$$

$$\frac{ds_z}{dt} = -\left(a + \frac{1}{\gamma} \right) F_r s_r$$

$$\frac{ds_\phi}{dt} = -s_r \dot{\phi},$$

Depolarization due to asynchron spin rotation

evolution of the beam polarization for zero emittance

$$\frac{|\Delta P|}{P_0} = \frac{(1 + s_{z0}^2)\sigma_r^2(\alpha\gamma_0\gamma)^{1/2}a^2}{8},$$

$$\frac{ds_r}{dt} = s_z\left(a + \frac{1}{\gamma}\right)F_r + s_\phi\dot{\phi}$$

$$\frac{ds_z}{dt} = -\left(a + \frac{1}{\gamma}\right)F_r s_r$$

$$\frac{ds_\phi}{dt} = -s_r\dot{\phi},$$

$\sigma_r = 0.5c/\omega_p$
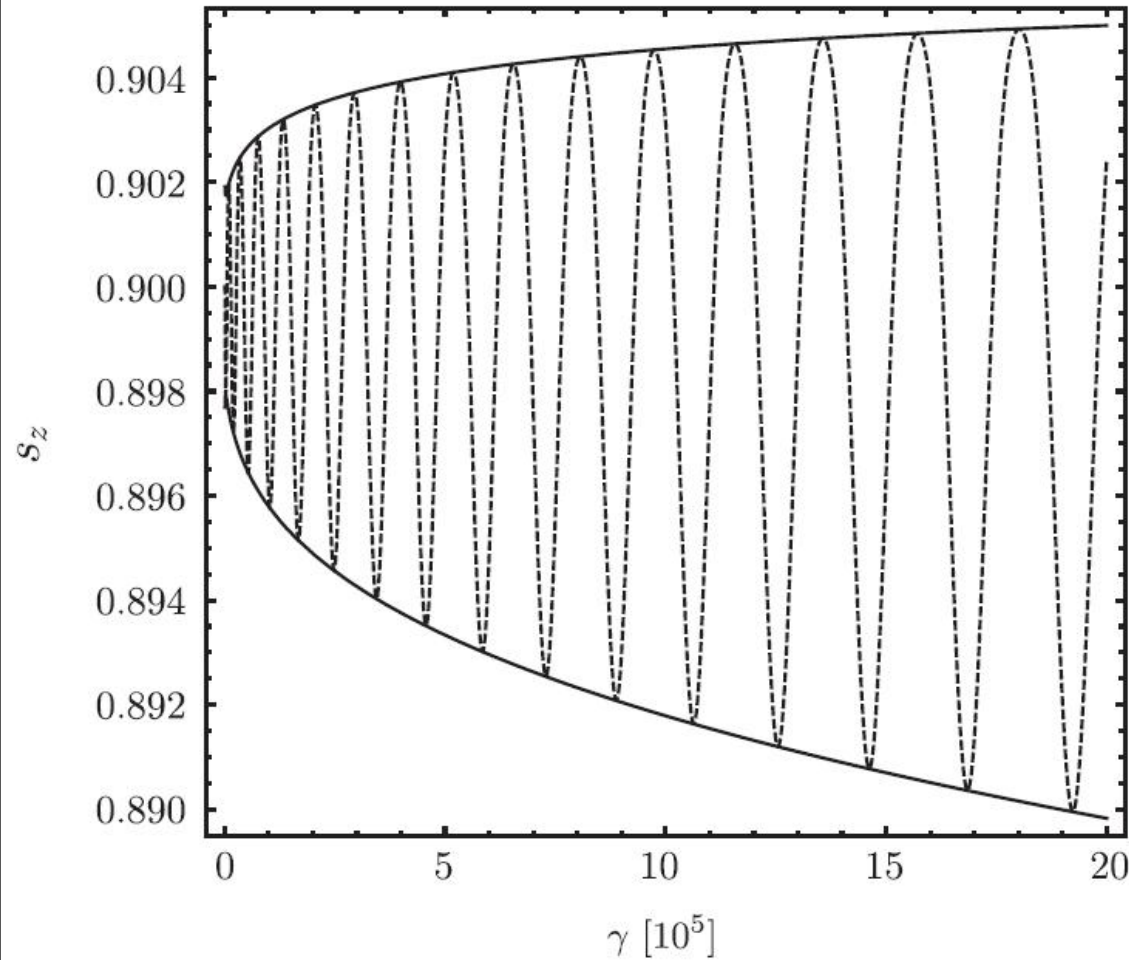
$\gamma_0 = 10^3$

$P_{z0}/P_0 = 0.9$
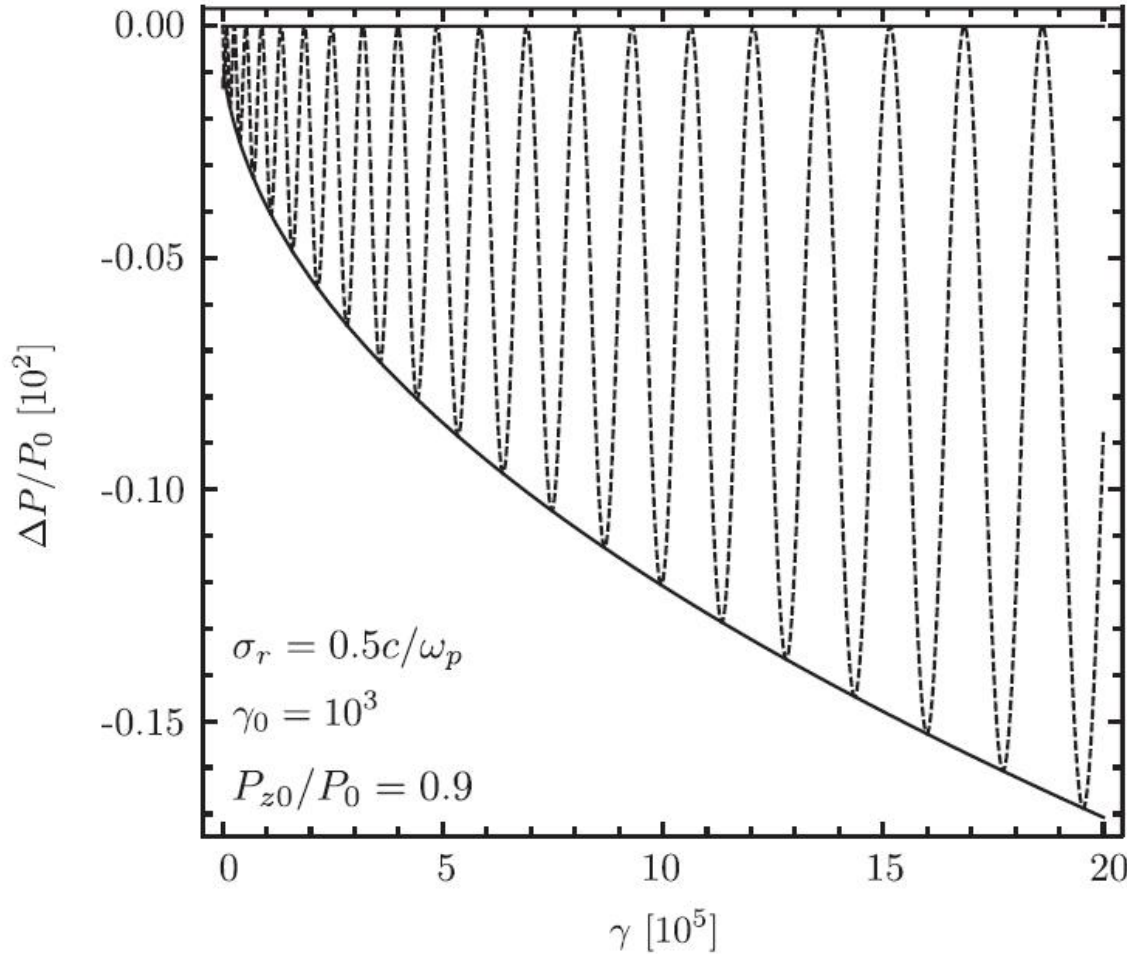
The Problem

The Source

The Coupling

The Acceleration

Summary

Depolarization due to asynchron spin rotation

evolution of the beam polarization for zero emittance

$$\frac{|\Delta P|}{P_0} = \frac{(1 + s_{z0}^2)\sigma_r^2(\alpha\gamma_0\gamma)^{1/2}a^2}{8},$$

a proper choice of the acceleration length can preserve the emittance

$$\frac{ds_r}{dt} = s_z\left(a + \frac{1}{\gamma}\right)F_r + s_\phi\dot{\phi}$$

$$\frac{ds_z}{dt} = -\left(a + \frac{1}{\gamma}\right)F_r s_r$$
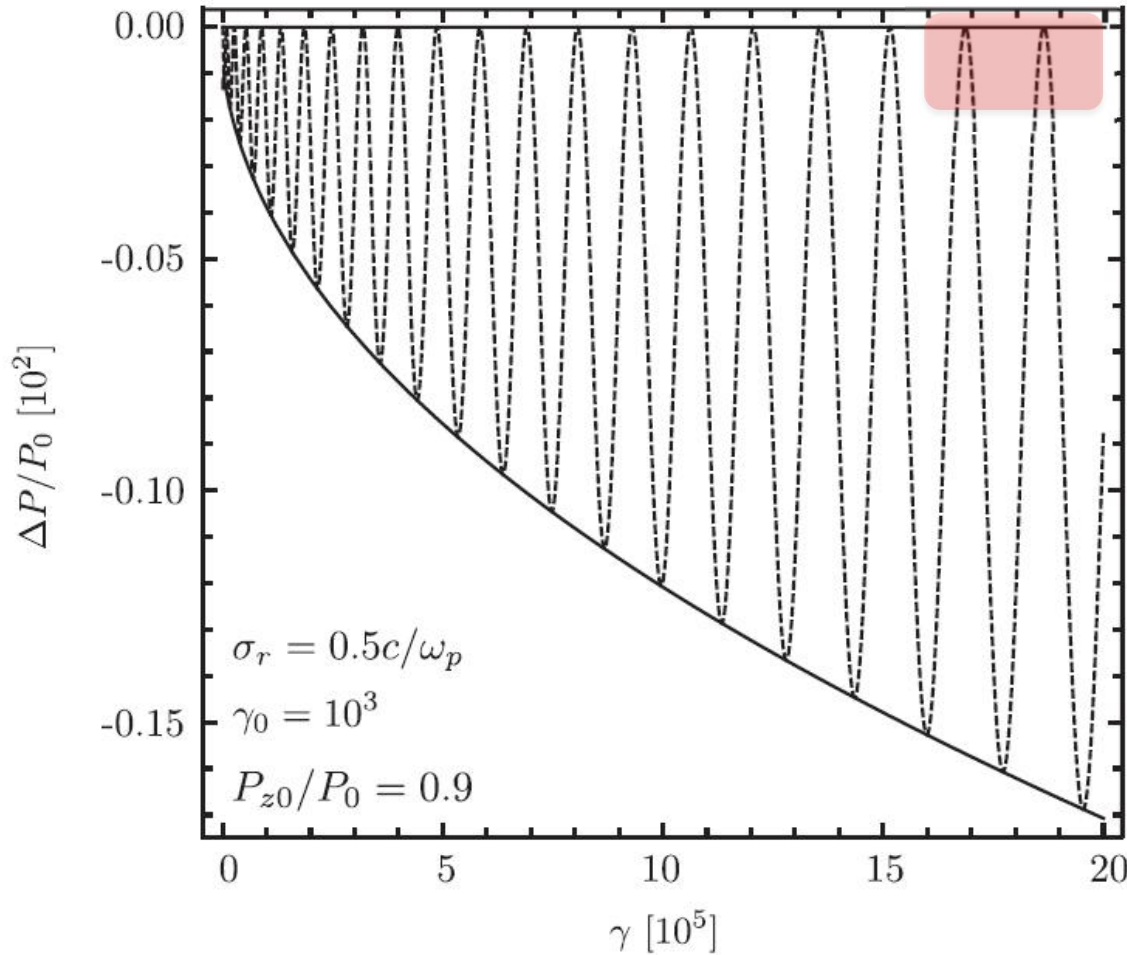
$$\frac{ds_\phi}{dt} = -s_r\dot{\phi},$$

$\sigma_r = 0.5c/\omega_p$

$\gamma_0 = 10^3$

$P_{z0}/P_0 = 0.9$

summary

- spin dependent scattering experiments are favourable

- acceleration of polarized beams is necessary

- pre-polarized targets are suitable as sources because:

  - conservation of initial polarization in coaxial LG pulse

  - up to 80% polarization maintained

  - simulations for energies in the range of 5 MeV

  - Gaussian beam destrois initial polarization immediately

- depolarization grows like squar root of energy

- fetching the bunch at the right energy can contain the polarization at TeV energies but:

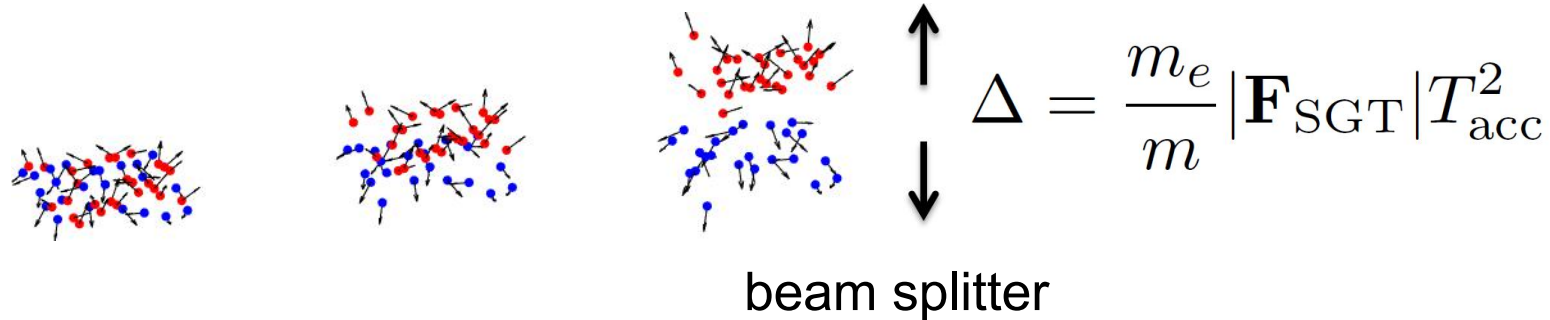 - radiation reaction and strong QED effects not jet included

The Problem

The Source

The Coupling

The Acceleration

Summary

Polarization due to field gradients

$$\Delta = \frac{m_e}{m}|\mathbf{F}_{\mathrm{SGT}}|T_{\mathrm{acc}}^2$$

beam splitter

$$\mathbf{F}_{\mathrm{SGT}} = \left(\nabla - \frac{d}{dt}\nabla_{\mathbf{v}}\right)(\mathbf{\Omega} \cdot \mathbf{s})$$

- displacement in field-gradient-free region due to the spin-change-rate caused by the T-BMT rotation

$$\Delta_e(\partial F = 0) \approx \Lambda_{\mathrm{SGT}}a_e\gamma T_{\mathrm{acc}}^2\epsilon^2.$$

- the temporal and spatial field variation separates two electron beams if

$$\partial F \ \gg \ a_e F^2$$

$$\Delta_e \approx \Lambda_{\mathrm{SGT}}T_{\mathrm{acc}}^2\epsilon^2\frac{\gamma}{2\pi}$$

- this formula holds for arbitrary field strength

$$\Lambda_{\mathrm{SGT}} = \frac{\hbar\omega_L}{2m_e c^2} \approx 1.2 \cdot 10^{-6}\lambda_L[\mu m]^{-1}$$

- no information about field onfiguration

Polarization due to spin flip
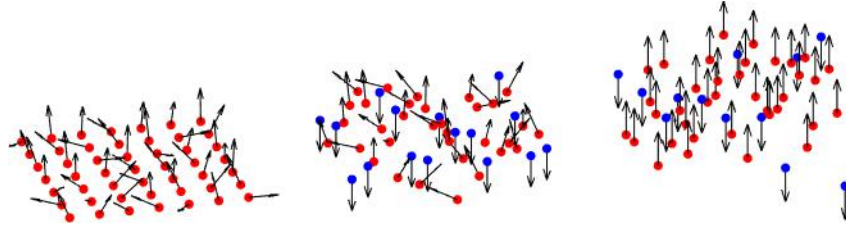
- coupling of spin to radiation field

- different possibility for spin-flip up than spin-flip down

- different transition rates

- build up of polarization along a certain axis

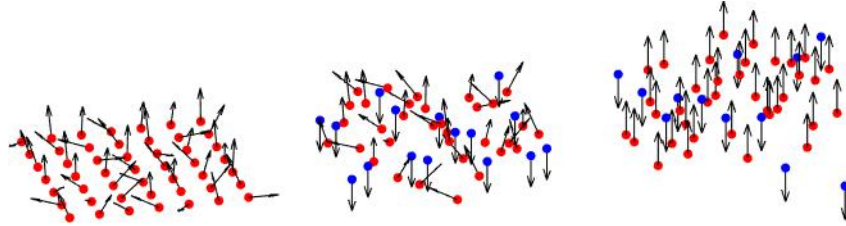# Polarization due to spin flip
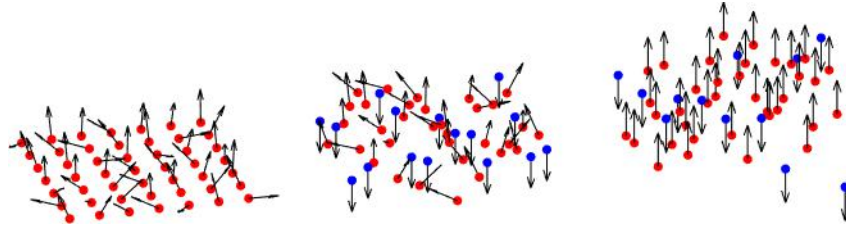
$$H_{\text{totoal}} = H_{\text{EM}} + H_{\text{SGT}} + H_{\text{RAD}} + H_{\text{ST}}$$

$$H_{\text{EM}} = \gamma m c^2 + q\varphi, \qquad\qquad H_{\text{SGT}} = \vec{\Omega} \cdot \mathbf{s},$$

$$H_{\text{RAD}} = q\varphi_{\text{rad}} - \frac{q}{c}\mathbf{v} \cdot \mathbf{A}_{\text{rad}}, \qquad H_{\text{ST}} = \vec{\Omega}_{\text{rad}} \cdot \mathbf{s}.$$

$$P(t) = P_{\text{eq}}[1 - \exp(-t/\tau_{\text{pol}})], \qquad P_{\text{eq}} = \frac{P_\uparrow - P_\downarrow}{P_\uparrow + P_\downarrow} \qquad \tau_{\text{pol}} = \frac{1}{P_\uparrow + P_\downarrow}$$

S. R. Mane, Phys. Rev. A 36, 105 (1987); Ya. S. Derbenev and A. M. Kondratenko, Zh. Eksp. Teor. Fiz. 64, 1918-1929 (1973)

Polarization due to spin flip

$$T_{\mathrm{pol}}^{-1} = \lim_{x \to 0} \alpha_+(x) = \frac{q^2 \hbar \gamma^5 |\dot{\mathbf{v}}|^3}{m^2 c^8} \frac{5\sqrt{3}}{8}$$

$$P_{\mathrm{eq}} = \lim_{x \to 0} \frac{\alpha_-(x)}{\alpha_+(x)} = -\frac{8}{5\sqrt{3}} = -0.92$$

S. R. Mane, Phys. Rev. A 36, 105 (1987); Ya. S. Derbenev and A. M. Kondratenko, Zh. Eksp. Teor. Fiz. 64, 1918-1929 (1973)