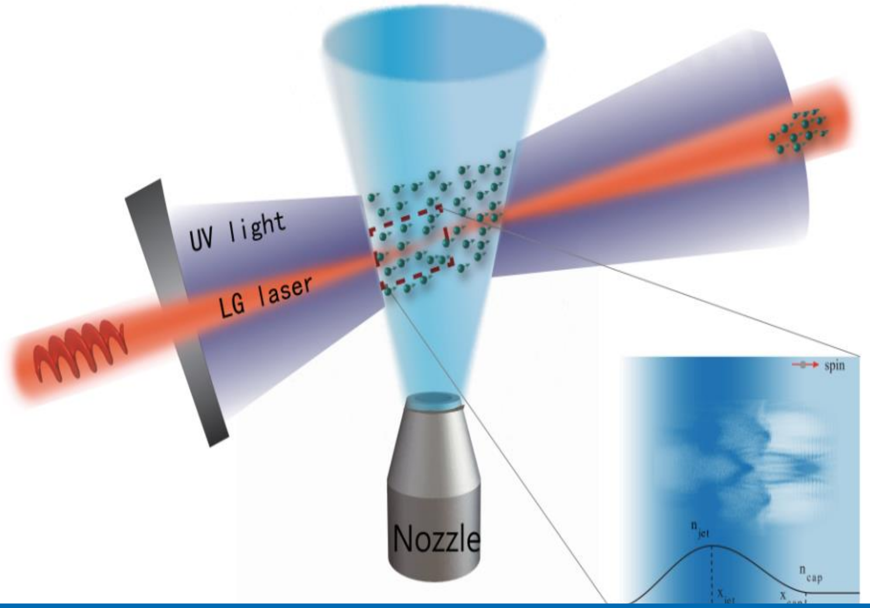


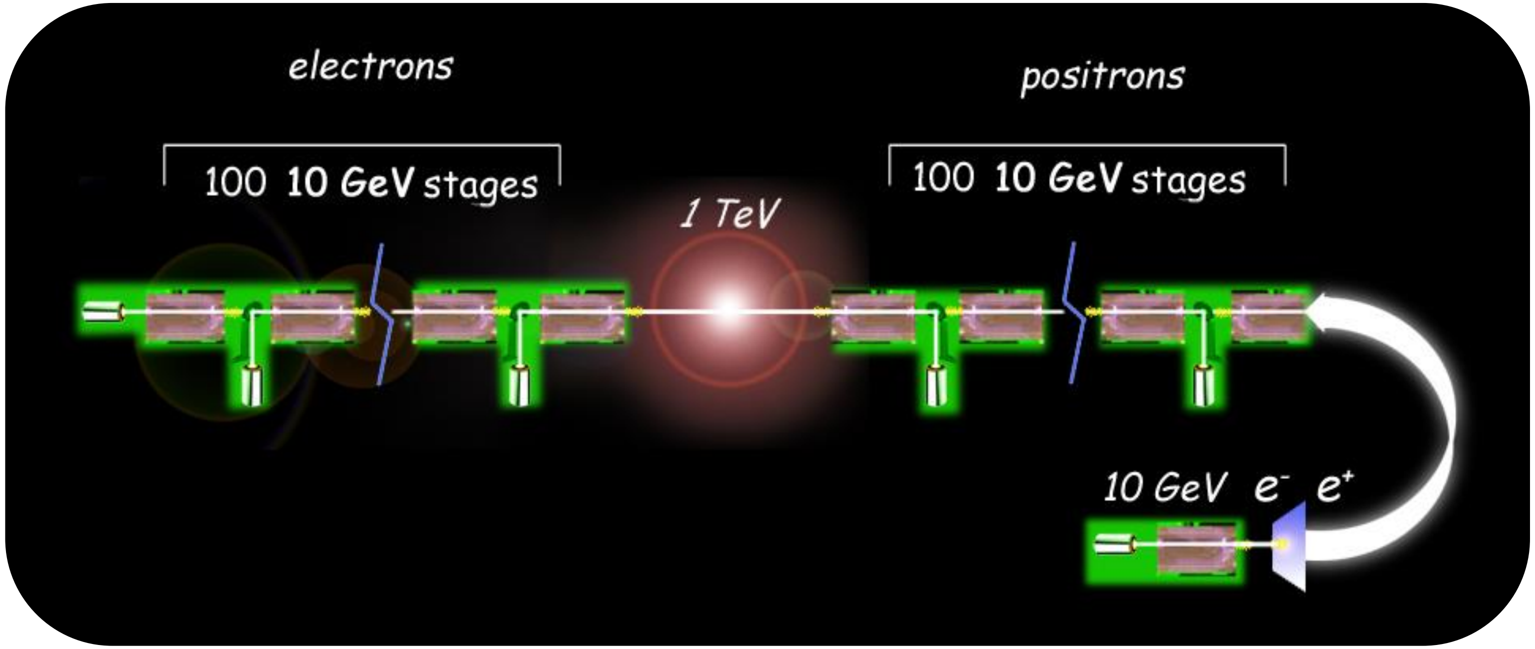
Simulations of electron and positron polarization preservation in plasma

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

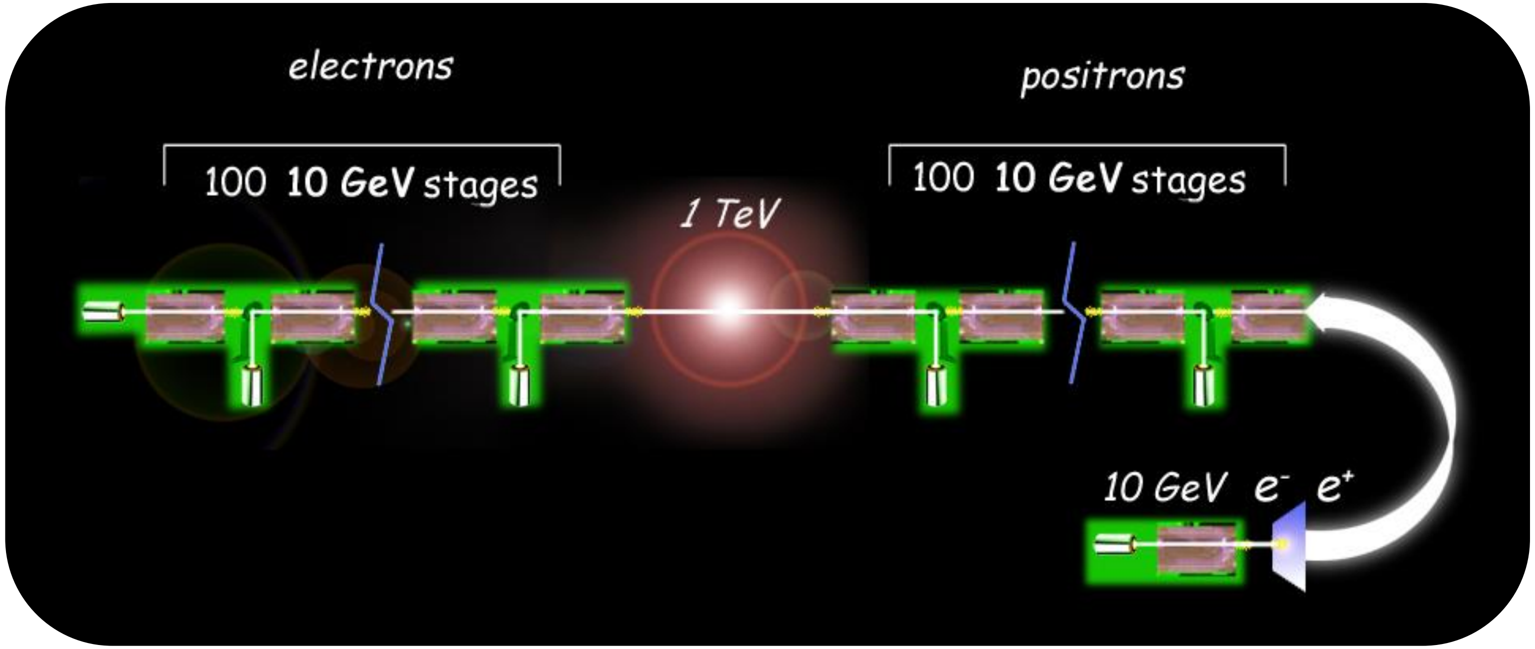


If you work on particle acceleration in plasma you think about:

- energy (maximum, spread)
- emittance (4D and 6D)
- beam charge and current
- repetition rate
- beam quality and luminosity
- plasma density
- transformer ratio
- staging, coupling, injection

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

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.

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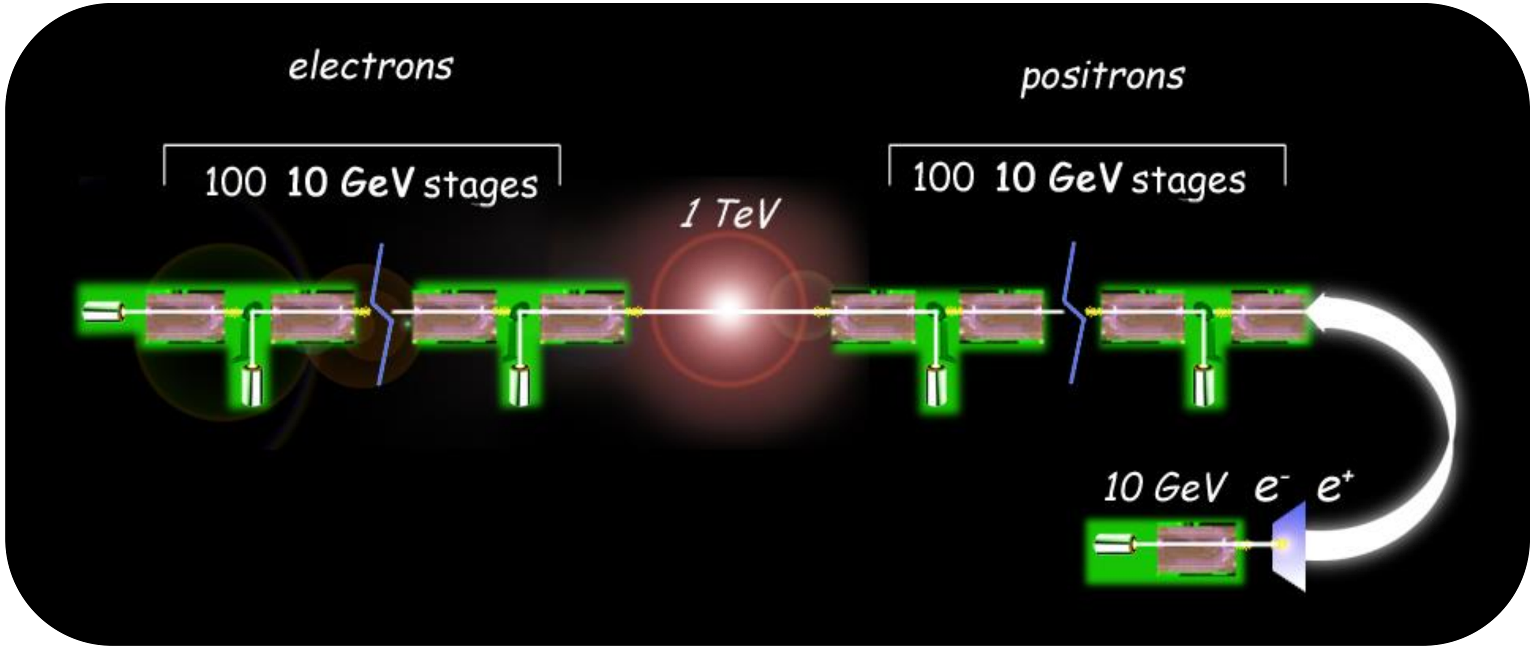

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The Problem

SOURCE

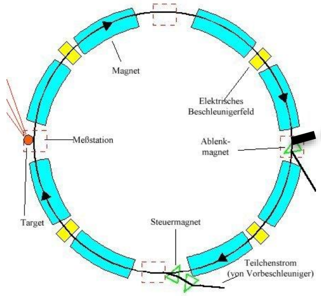
- gas target where the electron spins are already aligned before laser irradiation
- pre-accelerated and pre-ionized bunches

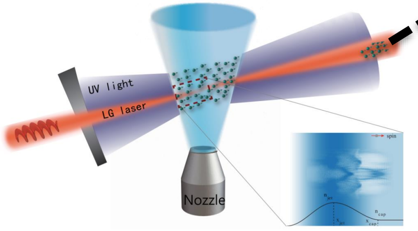
COUPLING

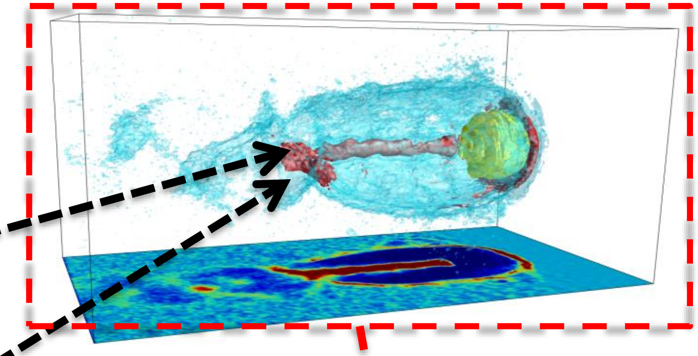
- polarization losses and emittance growth must be minimized
- bunch charge must be maximized

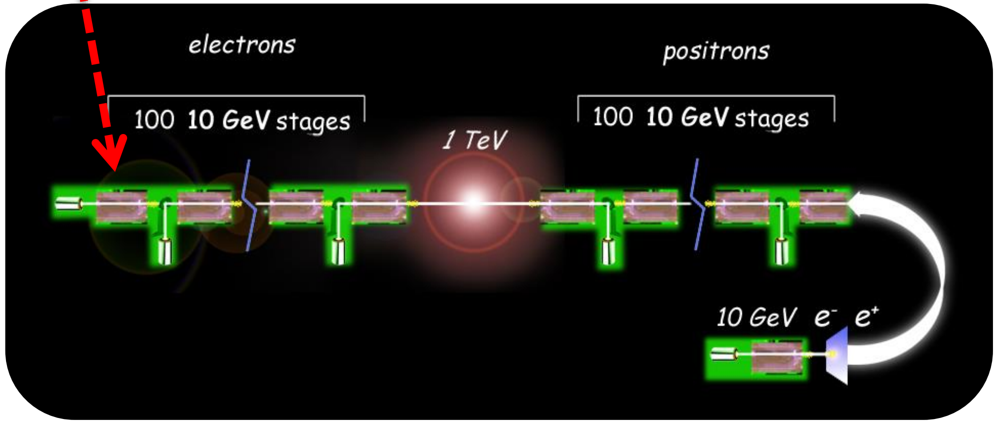
ACCELERATION

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







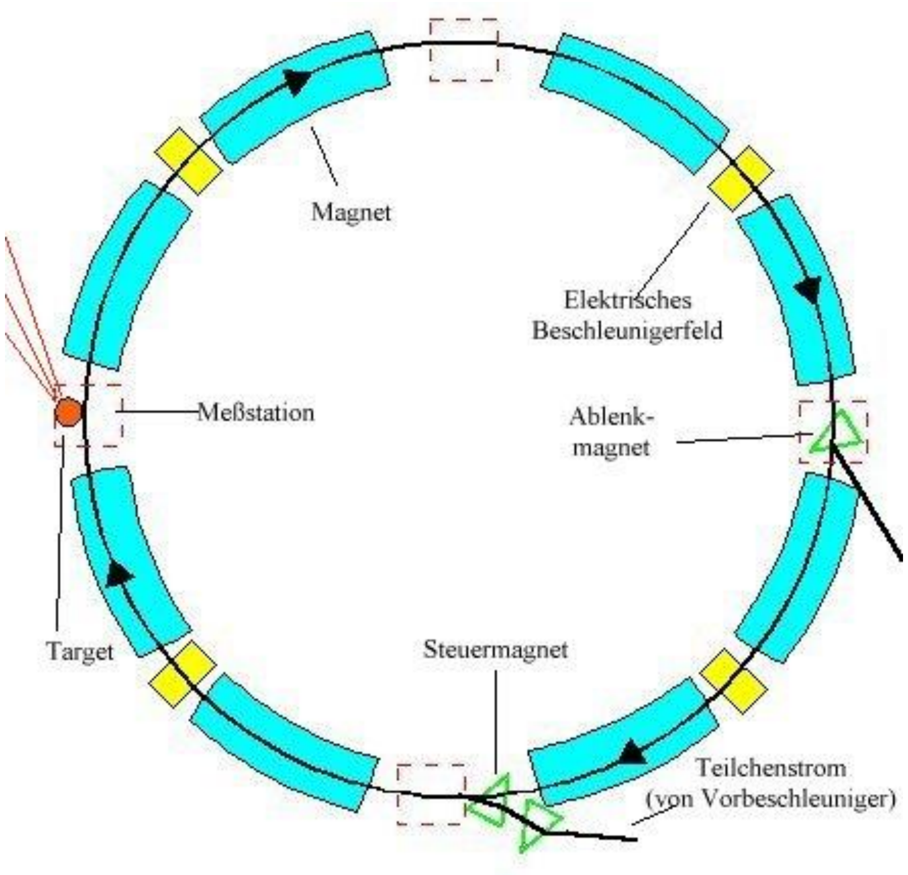


Paul Preuss, LBNL, Accelerators and Light Sources of Tomorrow (2009); Wu et al, submitted to nat. com.

The Source

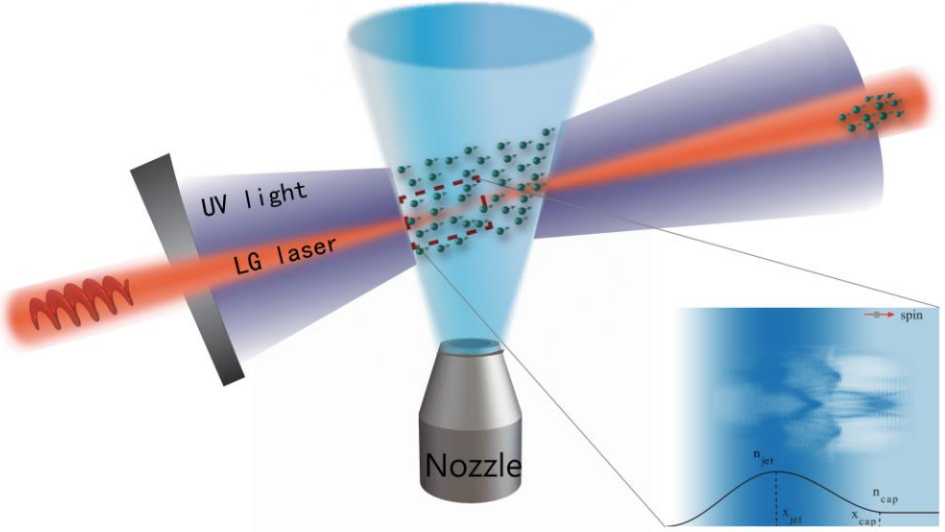
1st option

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



2nd option

Spin-polarized particle beams from laser-plasma accelerators

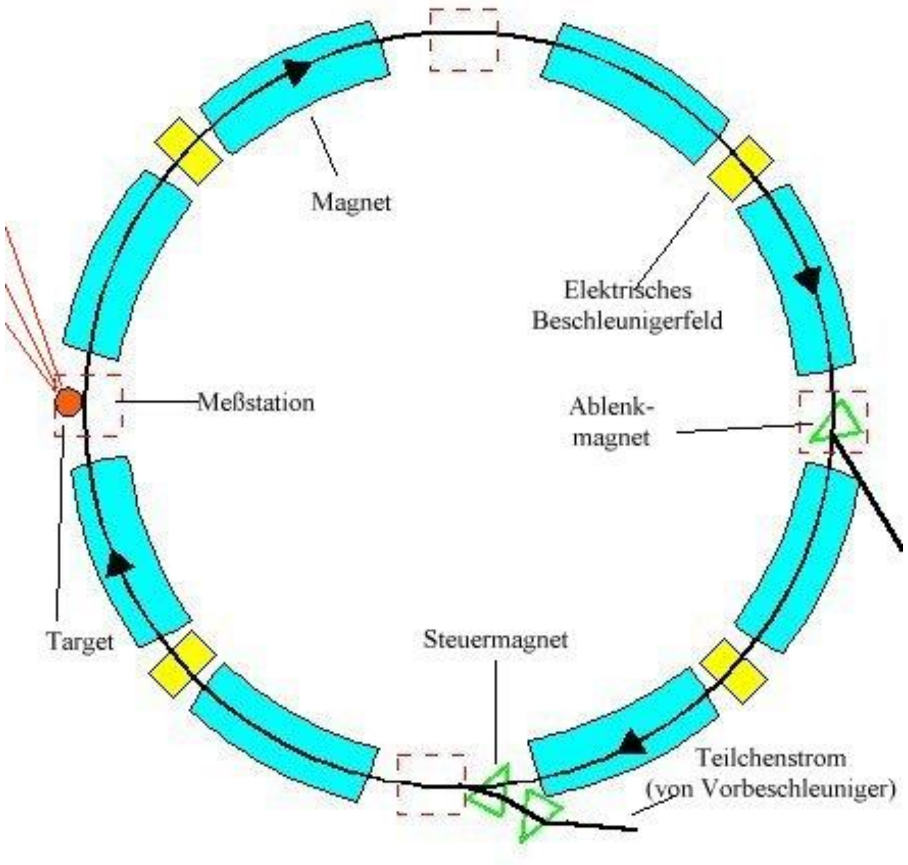


Wu et al, submitted to nat. com.

The 1st Source

1st option

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



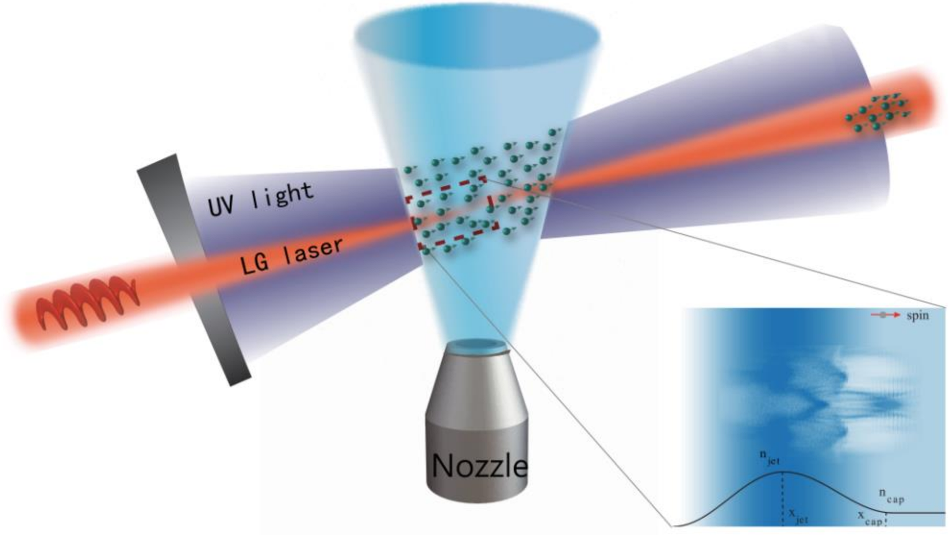
- achievable polarization: up to 92%
- energy in the GeV range
- polarization time for electrons in the range of minutes to hours
- storage-ring length in the km range

E. Gianfelice-Wendt et al, IPAC2018, doi:10.18429/JACoW-IPAC2018-MOPMF071

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

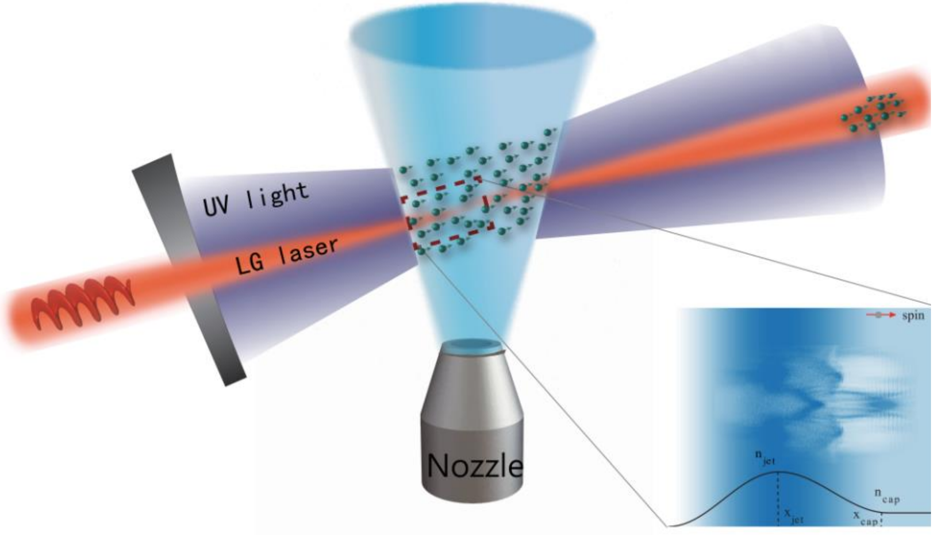
Wu et al, submitted to nat. com.

The 2nd Source

The Problem
The Source
The Coupling
The Acceleration
Summary

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]

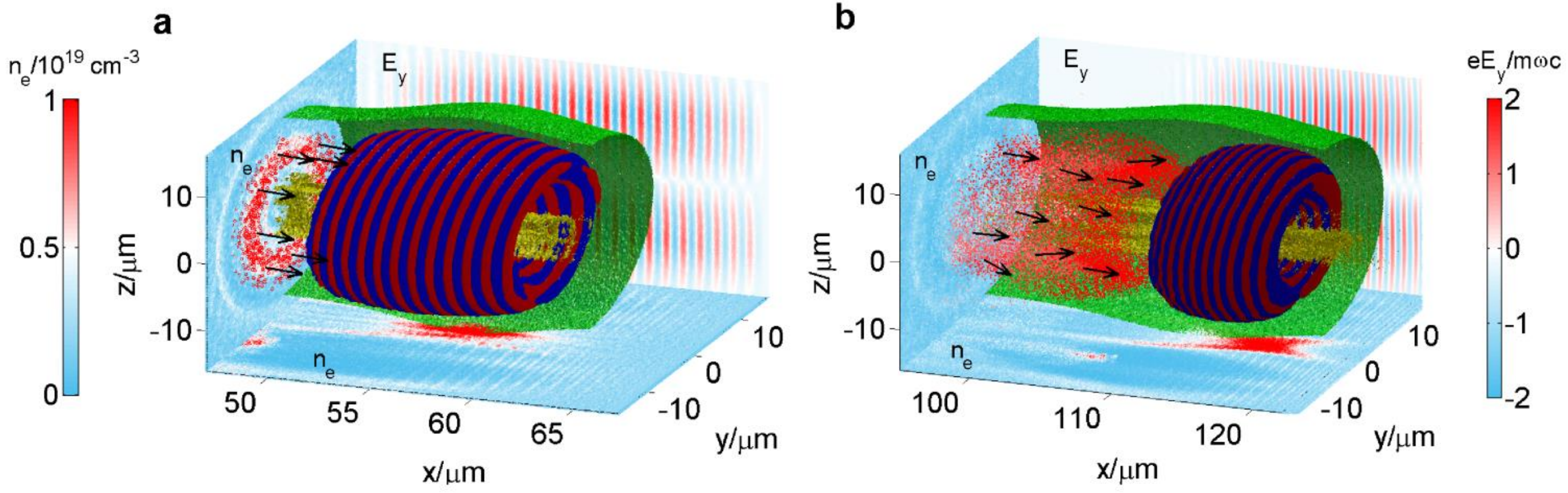
$$\vec{\Omega} = \frac{q}{mc}\left[\Omega_B \mathbf{B} - \Omega_v \left(\frac{\mathbf{v}}{c}\cdot\mathbf{B}\right)\frac{\mathbf{v}}{c} - \Omega_E \frac{\mathbf{v}}{c} \times \mathbf{E}\right],$$

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).

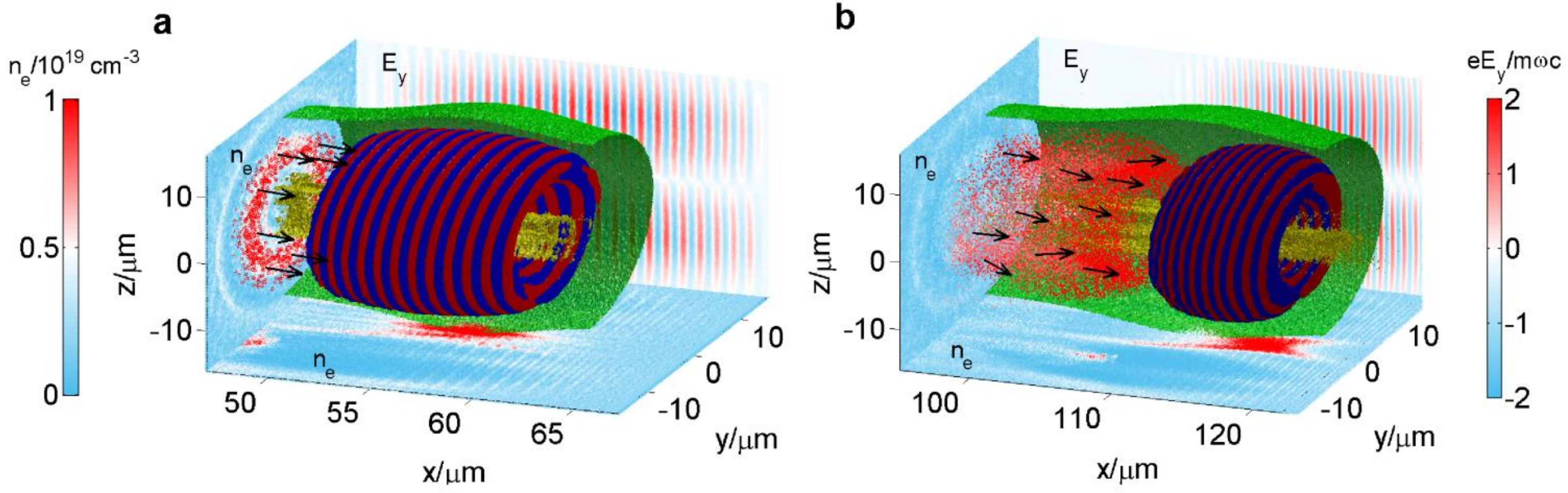
The 2nd Source



- 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

Wu et al, submitted to nat. com.

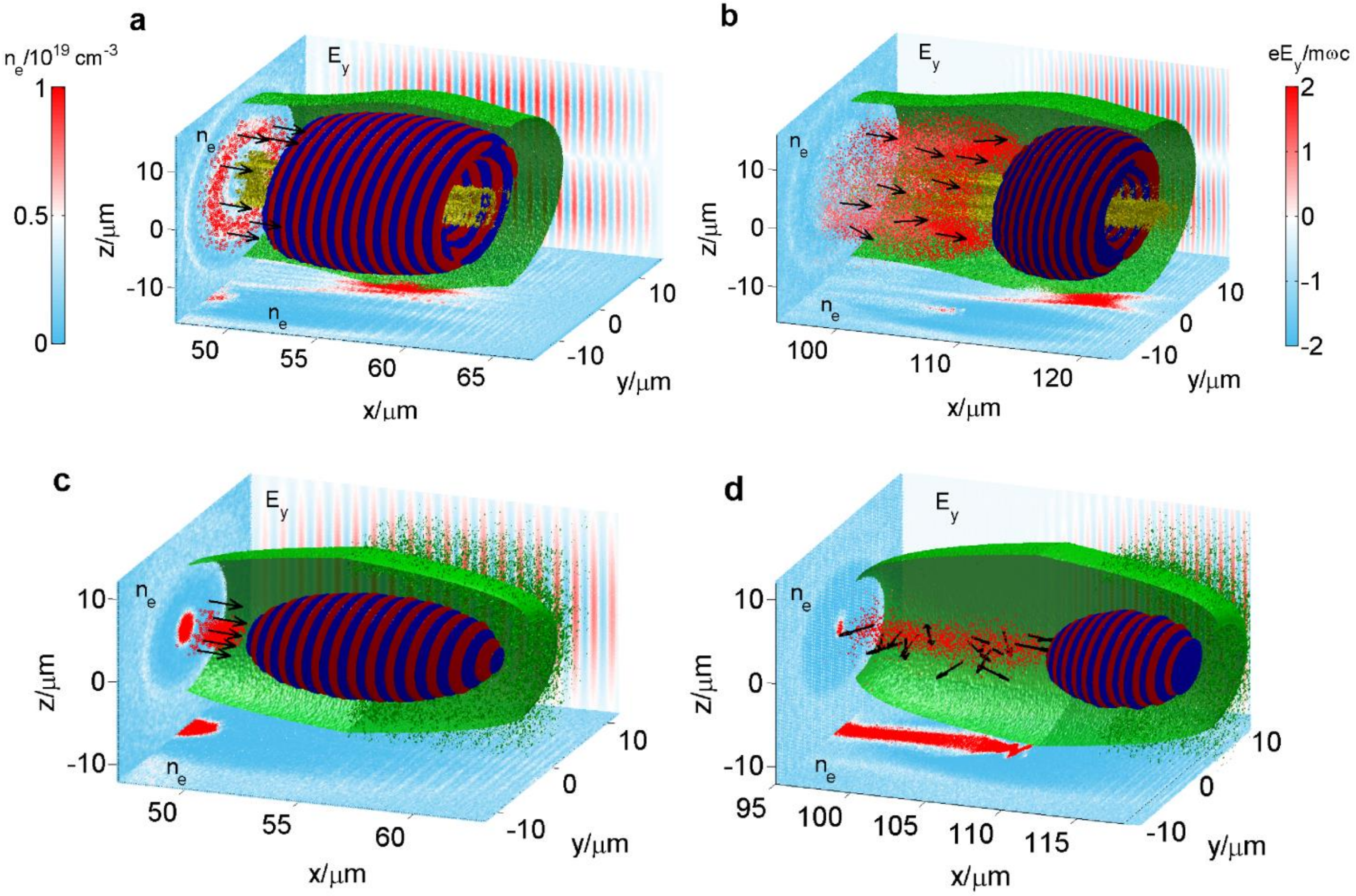
The 2nd Source



- 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.

The 2nd Source



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

The Problem

The Source

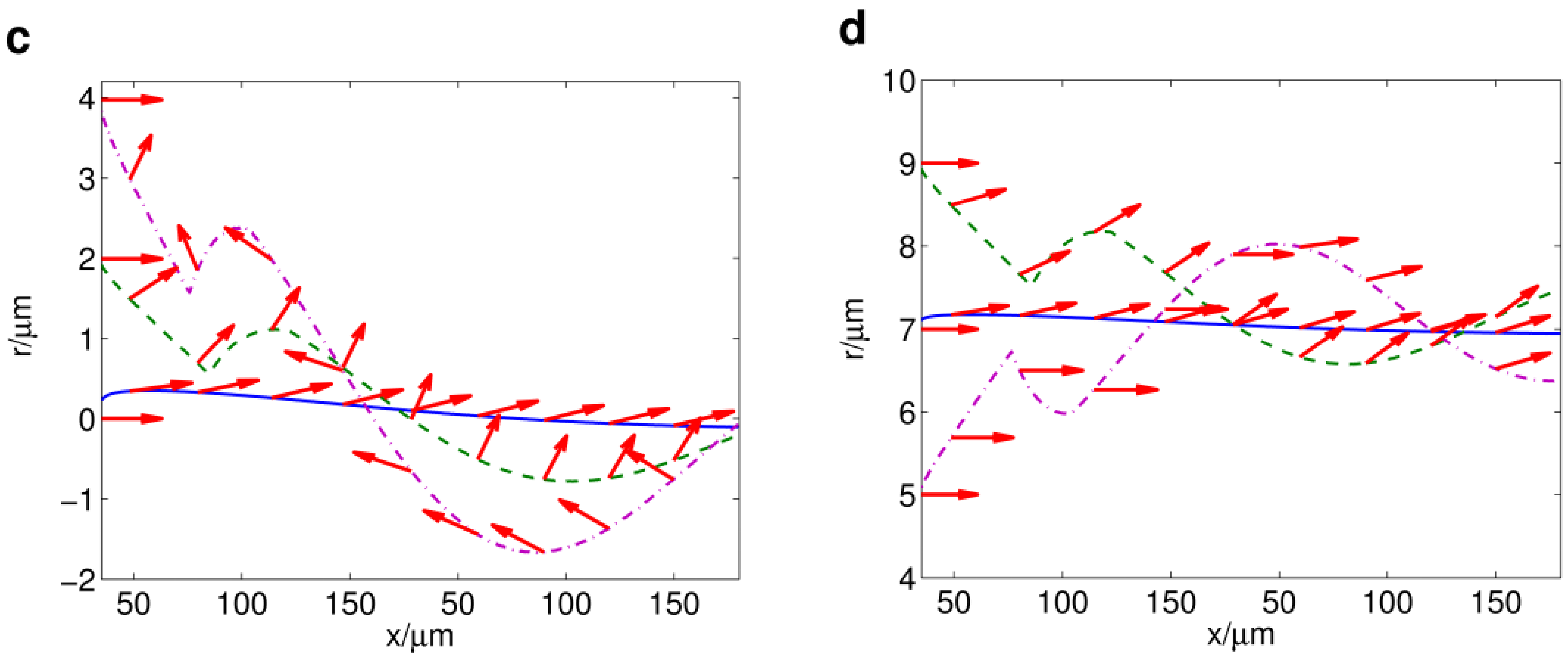
The Coupling

The Acceleration

Summary

Wu et al, submitted to nat. com.

The 2nd Source

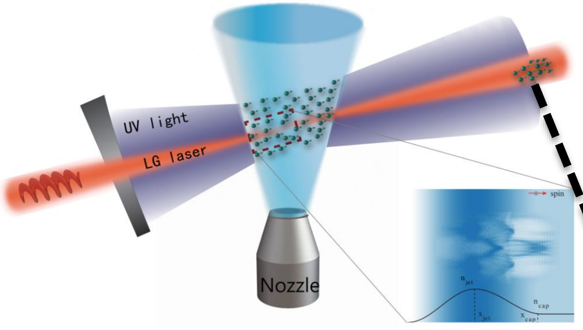


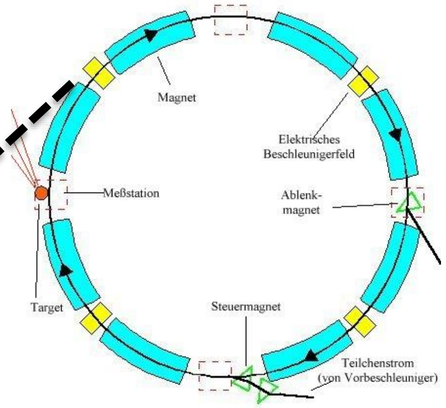
LEFT: in the Gaussian case, the electron spins oscillate incoherently at high frequencies and lose their initial spin orientations instantly

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

Wu et al, submitted to nat. com.

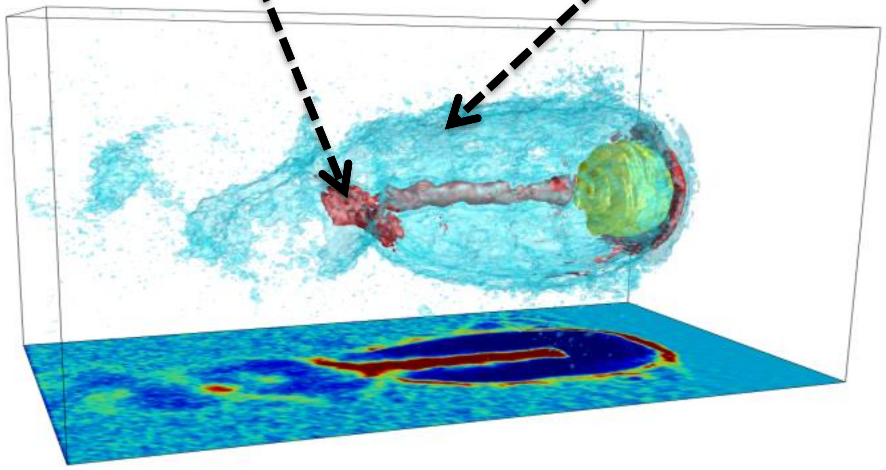
The Coupling





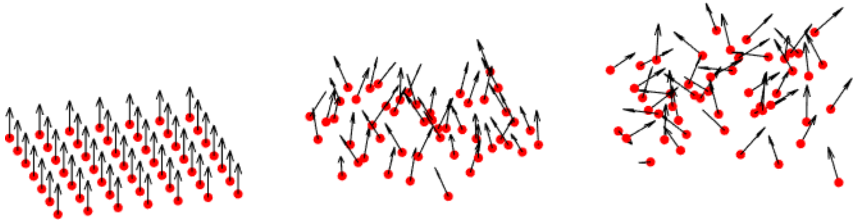
- staging at the MeV level

- lateral injection
- on axis

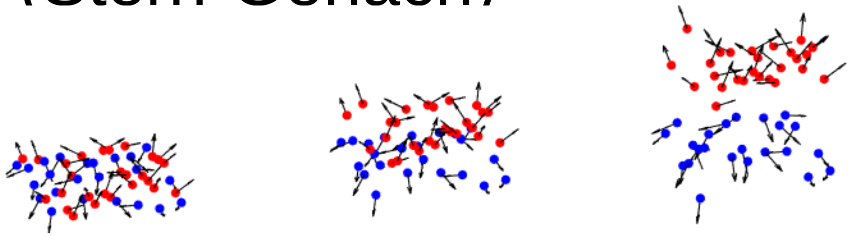


Possible (De-)Polarization mechanisms

- (asynchrone) spin rotation described by the T-BMT equation



- beam splitter (Stern-Gerlach)



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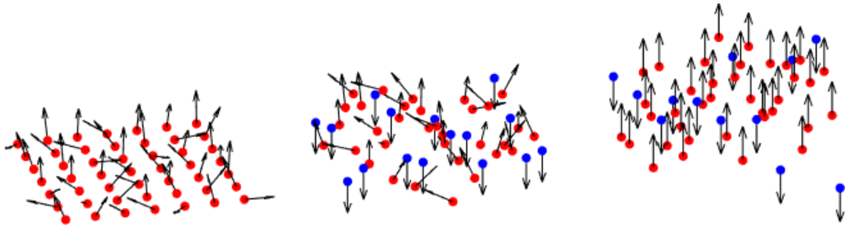

Anna Hützen et al. , HPL_SE 7 E6 (2019) ; J. Thomas et al., publication in preparation for Phys. Rev. Accel. Beams

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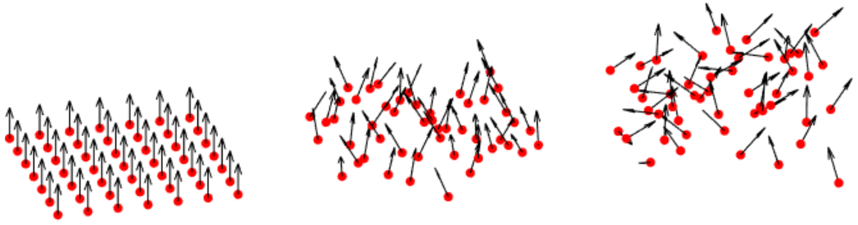
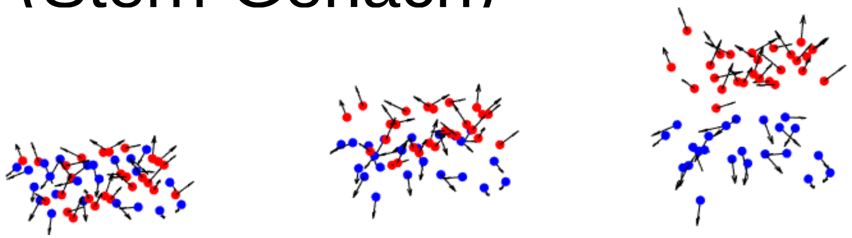


implemented in PIC, fluid and quasi-static codes

- beam splitter (Stern-Gerlach)



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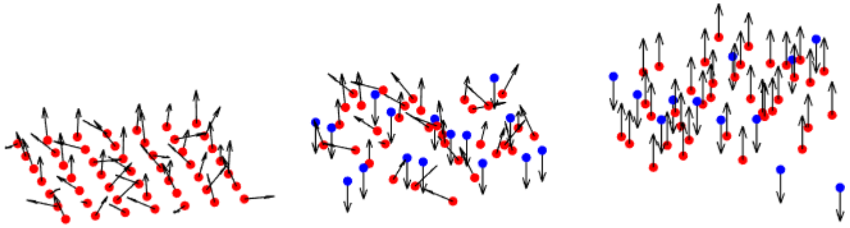
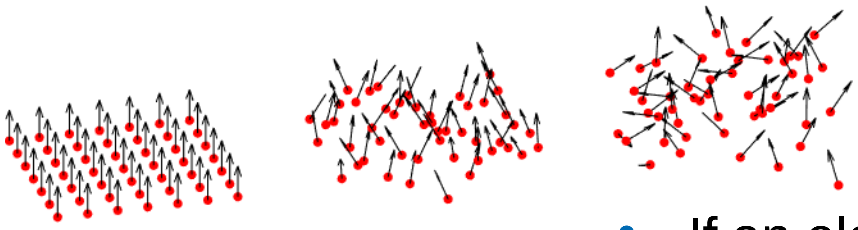


always discussed away:

- SGT is weaker than Lorenz force
- ST is coupled to radiation which is neglegible

Anna Hützen et al. , HPL_SE 7 E6 (2019) ; J. Thomas et al., publication in preparation for Phys. Rev. Accel. Beams

Depolarization due to asynchron spin rotation



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

In cgs units the rotation frequency is simply [10]

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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?

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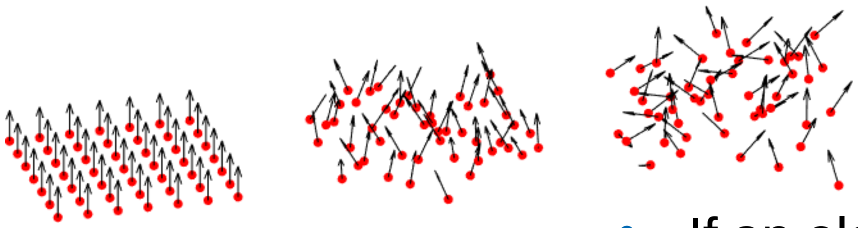

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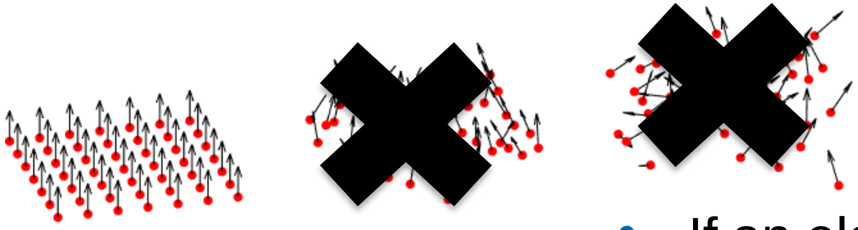

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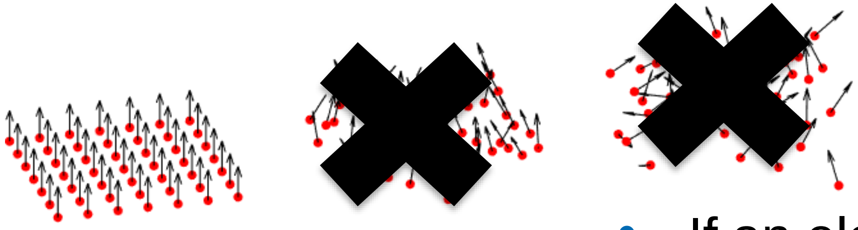

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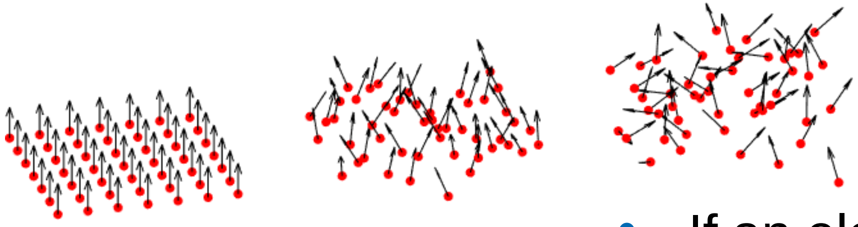

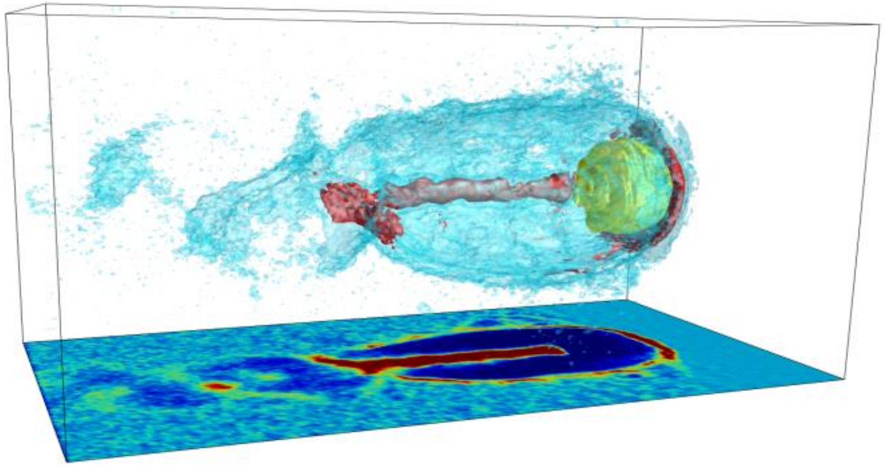

- inside the laser
- in the wake
- in the bunch
- in front of the laser
- in the sheath

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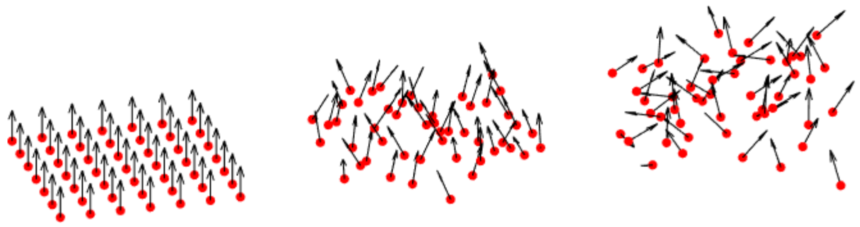

$$T_{D,e} \propto \frac{\pi}{2\Omega_{e,GeV}} = \frac{\pi}{6a_e F}$$

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

J. Thomas et al., publication in preparation for Phys. Rev. Accel. Beams; J. Vieira, PRST_AB 14, 071303 (2011)

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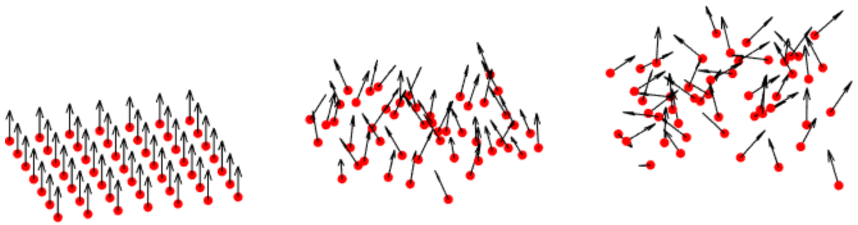

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$$\mathbf{E} = E_r \mathbf{e}_r + E_z \mathbf{e}_z$$

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

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

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

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

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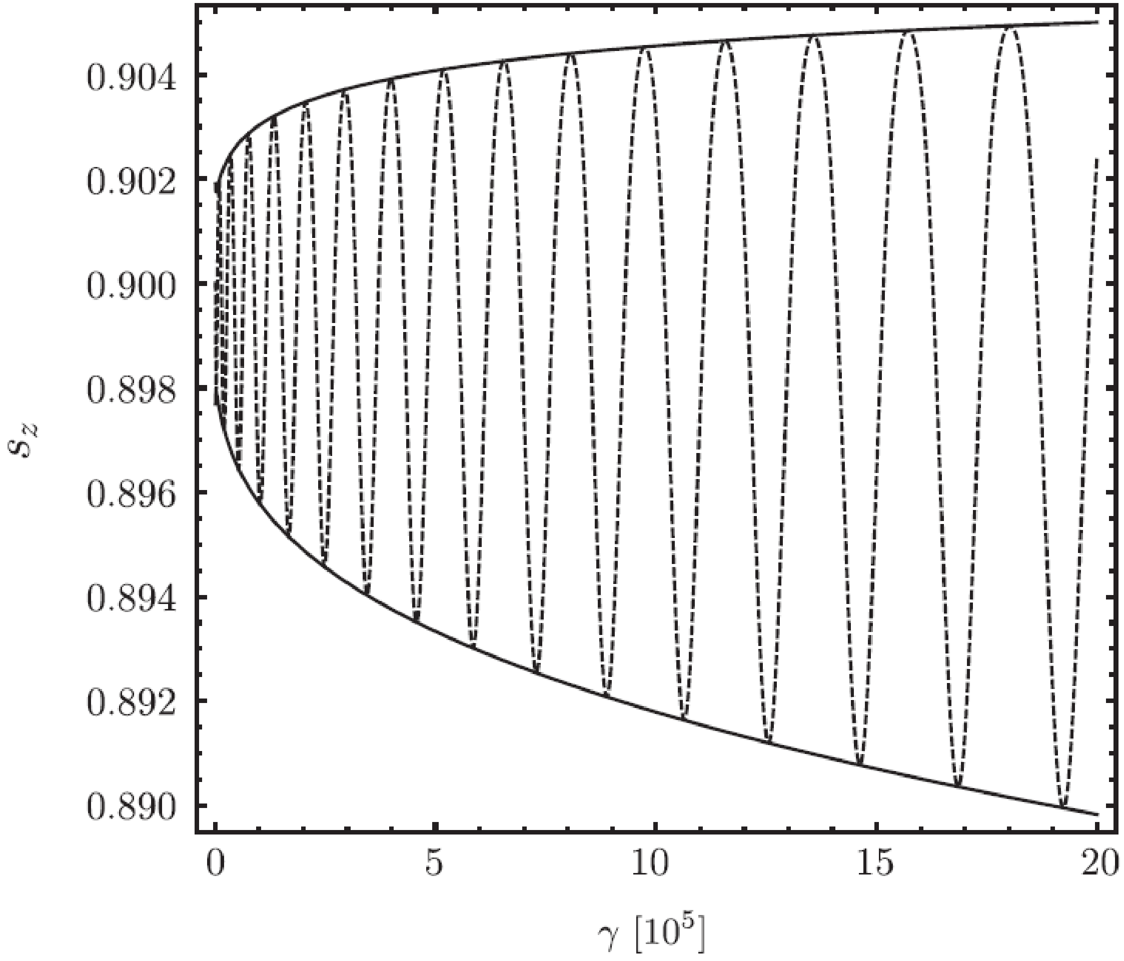
Depolarization due to asynchron spin rotation

sumilation of single particle spin



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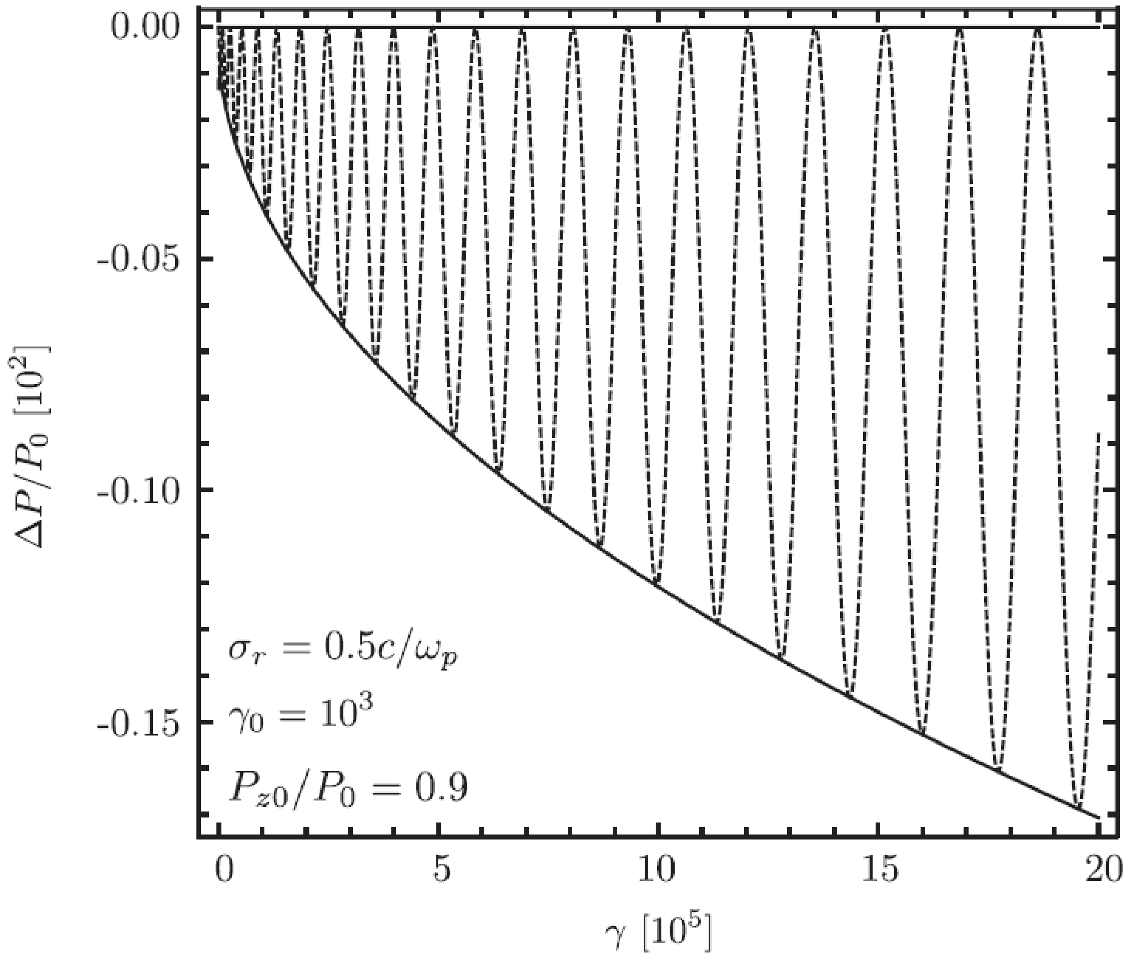
Depolarization due to asynchron spin rotation

HEINRICH HEINE UNIVERSITÄT DÜSSELDORF

evolution of the beam polarization for zero emittance



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

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

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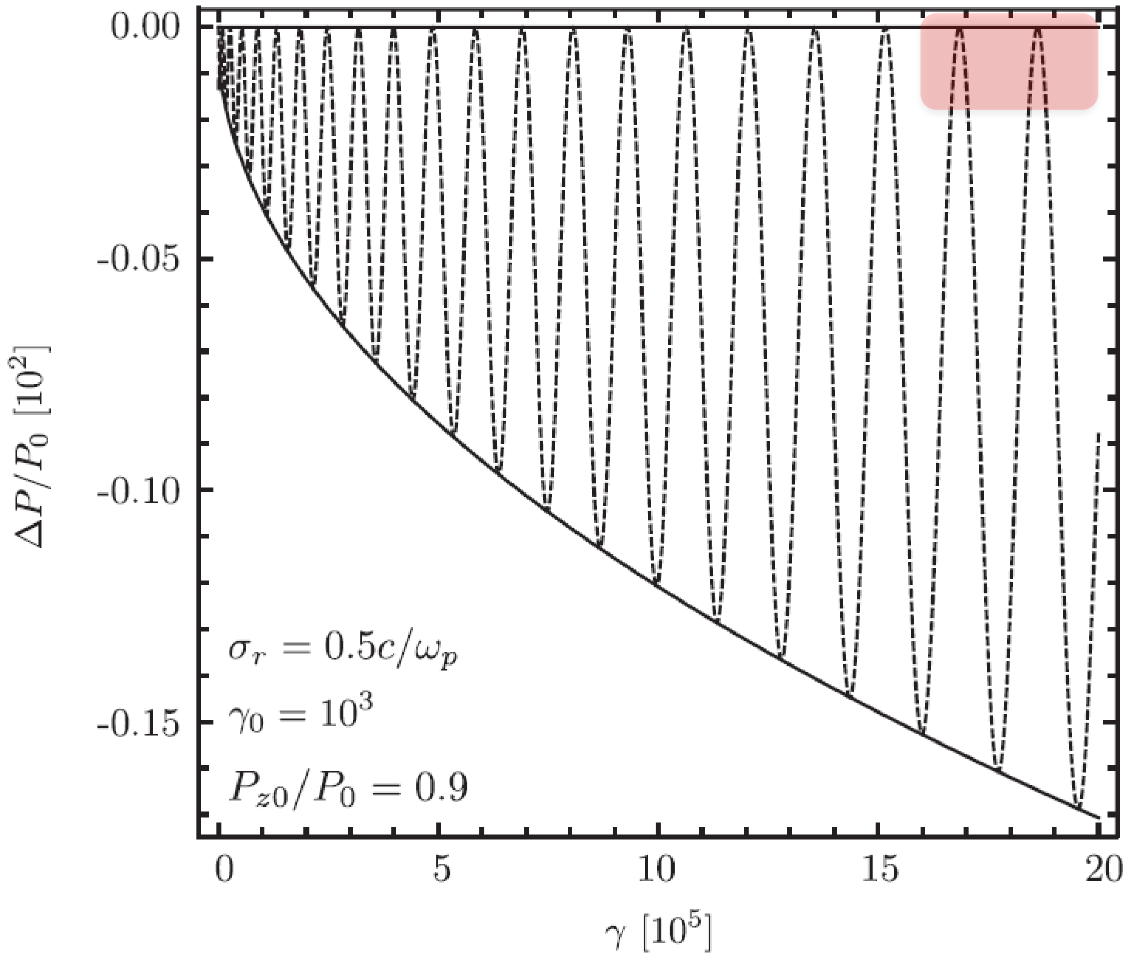

$$\frac{|\Delta P|}{P_0} = \frac{(1+s_{z0}^2)\sigma_r^2(\alpha\gamma_0\gamma)^{1/2}a^2}{8},$$

a proper choice of the acceleration length can preserve the emittance

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

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

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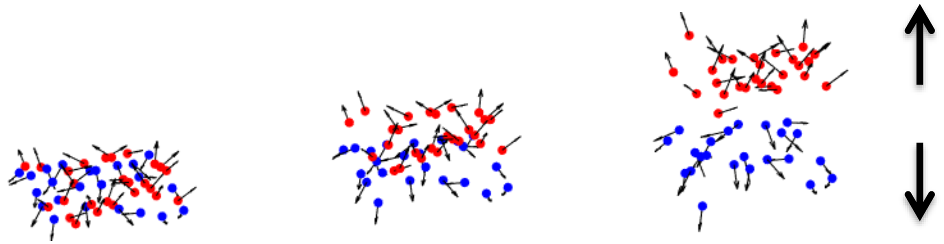
J. Vieira, PRST_AB 14, 071303 (2011)

- 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

Polarization due to field gradients



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

beam splitter

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

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

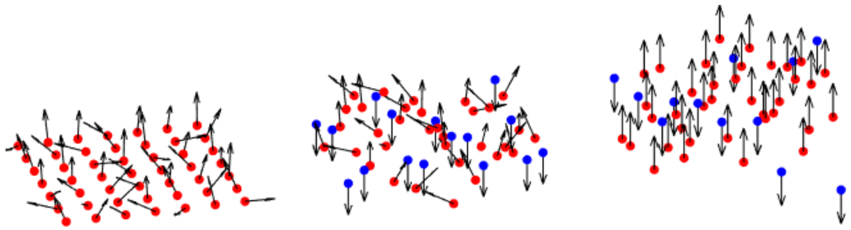
$$\Delta_e \approx \Lambda_{\mathrm{SGT}} T_{\mathrm{acc}}^2 \epsilon^2 \frac{\gamma}{2\pi}$$

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

- displacement in field-gradient-free region due to the spin-change-rate caused by the T-BMT rotation
- the temporal and spatial field variation separates two electron beams if
  $$\partial F \gg a_e F^2$$
- this formula holds for arbitrary field strength
- no information about field onfiguration

Anna Hützen et al. , HPL_SE 7 E6 (2019) ; J. Thomas et al., publication in preparation for Phys. Rev. Accel. Beams

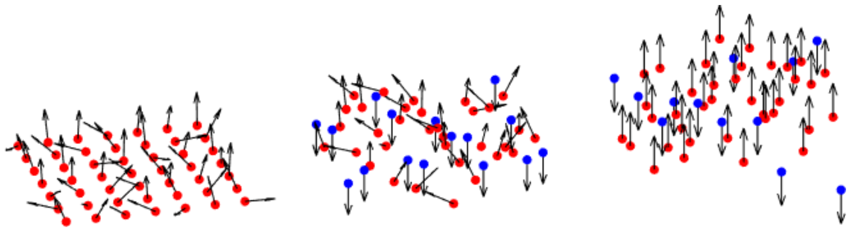
Polarization due to spin flip



- 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

Anna Hützen et al. , HPL_SE 7 E6 (2019) ; J. Thomas et al., publication in preparation for Phys. Rev. Accel. Beams

Polarization due to spin flip



$$H_{\text{totoal}} = H_{\text{EM}} + H_{\text{SGT}} + H_{\text{RAD}} + H_{\text{ST}}$$

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

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

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

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

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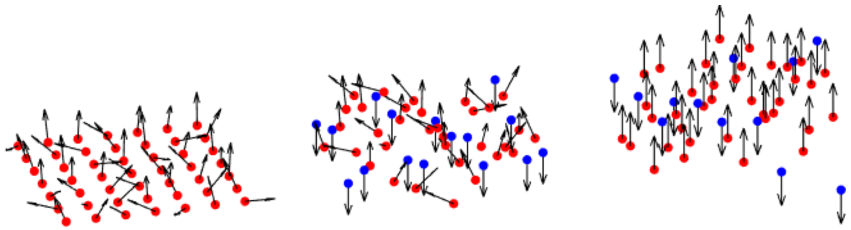

$$T_{\mathrm{pol}}^{-1} = \lim_{x\to 0} \alpha_+(x) = \frac{q^2\hbar\gamma^5|\dot{\mathbf{v}}|^3}{m^2c^8}\frac{5\sqrt{3}}{8}$$

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

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