Spin effects in strong laser and plasma fields

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NSFC、CAS-SPRP（中科院先导B）、HGF-ATHENA
Contents

- Introduction of the laser facilities
- Spin effects in the SF-QED regime
- Generation of polarized particle sources
- Conclusions
**Shanghai Light Source**

**SULF 10PW**

**SEL 100PW**

**ShanghaiTech University**

**Shanghai XFEL (SHINE)**

**XFEL parameters:**
- e-beams: 8-10 GeV
- Photons: 0.4-25 keV
- Rep.rate: 1 MHz
Shanghai Ultra-short and ultra-intense laser facility (SULF, 10PW)

1PW beamline: 30J, 30fs, 0.1Hz

10PW beamline: 250J, 25fs

- **DMEC**: Dynamics of Materials under Extreme Conditions
- **USAP**: Ultrafast Sub-atomic Physics
- **MODEC**: Big Molecule Dynamics and Extreme-fast Chemistry
10PW-200PW laser facilities worldwide

- Under construction 10PW-class
- Proposal 100PW-class

- Rochester 75PW
- Vulcan 10PW
- Apollon 10PW
- ELI 200PW
- ELI 10PW
- XCELS 200PW
- XCELS 10PW
- SULF 10 PW
- SEL 100PW
- SGII 5PW
- APRI 4PW
- Gekko EXA 100PW
- SILEX 5PW
Station of Extreme Light (SEL, 100PW)

- Located in the Farthest shaft
- 35 meters underground.
- Flexible interaction-angles
### Parameters for proposed experiments in SEL

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Nominal</th>
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<tbody>
<tr>
<td><strong>X-ray</strong></td>
<td></td>
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<tr>
<td>Photon Energy</td>
<td>3 - 15 keV</td>
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<tr>
<td>Photons per pulse</td>
<td>$10^{11-12}$</td>
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<tr>
<td>Pulse length</td>
<td>20-50 fs</td>
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<tr>
<td>beam spot size</td>
<td>0.2-5 μm</td>
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<tr>
<td>Energy Resolution</td>
<td>0.6 eV</td>
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<tr>
<td><strong>Laser</strong></td>
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<tr>
<td>Focused intensity</td>
<td>$1\times10^{23}$ W/cm$^2$</td>
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<tr>
<td>Peak power</td>
<td>100 PW</td>
</tr>
<tr>
<td>Repetition rate</td>
<td><a href="mailto:1Hz@0.1-1PW">1Hz@0.1-1PW</a></td>
</tr>
<tr>
<td></td>
<td>Single shot@100PW</td>
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</table>

- Pulse energy 1500J; duration 15fs; Central wavelength 900nm; Peak power 100 PW; Focused spot size 5μm; Intensity >$10^{23}$ W/cm$^2$; Contrast ratio >$10^{12}$
In SEL, the 100PW laser will collide with the XFEL beam, probing “vacuum birefringence” for the first time.

In QED, vacuum is full of virtual particle pairs that can mediate light-light interaction forbidden in classical theory.
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Laser intensity VERSUS interaction regimes

With 10-100PW laser, light intensity reaches beyond $10^{22}\text{W/cm}^2$, light-matter interaction steps into the new Radiation-dominated & QED regime.

OPN July(2011); Science 331, 41 (2011); Nature Material 15, 1(2016)
Extreme-field effects

QED cascade

Radiation-reaction trapping


Quantum behavior of relativistic particles in strong laser field

Landau-Lifschitz Equation

\[
\frac{dp}{dt} = e(\mathbf{E} + \frac{1}{c} \mathbf{v} \times \mathbf{B}) + \frac{2e^3}{3mc^4} \gamma \left\{ \frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \right\} \mathbf{E} + \frac{1}{c} \mathbf{v} \times \left( \frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \right) \mathbf{B} + \frac{2e^4}{3mc^4} \mathbf{E} \times \mathbf{B} + \frac{1}{c} \mathbf{B} \times (\mathbf{B} \times \mathbf{v}) + \frac{1}{c} \mathbf{E} (\mathbf{v} \cdot \mathbf{E}) - \frac{2e^4}{3mc^4} \gamma^2 \mathbf{v} \left( (\mathbf{E} + \frac{1}{c} \mathbf{v} \times \mathbf{B})^2 - \frac{1}{c^2} (\mathbf{E} \cdot \mathbf{v})^2 \right)
\]

L.D. Landau & E.M. Lifshitz, 1971

Laser: $5 \times 10^{22}$ W/cm$^2$
Electron: 500 MeV

Stochastic Photon emission

Emitting intensity

\[
W_{ph} = \frac{2m_e^2c^4}{3\sqrt{3\pi\hbar^2}} \int_0^\infty dx \frac{5x^2 + 7x + 5}{(1 + x)^3} K_{2/3} \left( \frac{2x}{3z} \right)
\]

Emitting probability

\[
I_{ph} = \frac{e^2m_e^4}{3\sqrt{3\pi^2\hbar^4}} \int_0^\infty dx \frac{x(4x^2 + 5x + 4)}{(1 + x)^4} K_{2/3} \left( \frac{2x}{3z} \right)
\]

J. Sov. Laser Res. 6(5), 497 (1985)

Communications Physics 2, 66 (2019)
Spin effects arise in the new regime

\( a: \) dimensionless laser amplitude

\( \chi: \) QED parameter

\[ \chi = \frac{e \hbar}{m^2 c^4} \sqrt{\left(\frac{\mathbf{p} \cdot \mathbf{E}}{c} + \mathbf{p} \times \mathbf{H}\right)^2 - (\mathbf{p} \cdot \mathbf{E})^2} \]
Spin dynamics: precession and deflection

Thomas-BMT equation

\[
\frac{ds}{dt} = \frac{e}{m} \left[ \left( a_e + \frac{1}{\gamma} \right) \mathbf{B} - \frac{a_e \gamma}{\gamma + 1} \left( \beta \cdot \mathbf{B} \right) \beta - \left( a_e + \frac{1}{\gamma + 1} \right) \beta \times \frac{\mathbf{E}}{c} \right] \times s
\]


The Stern-Gerlach force

\[
F_{SG} = \nabla (\mu \cdot \mathbf{B})
\]


Non-radiative

The Stern-Gerlach experiment[1]
Spin dynamics: The Sokolv-Ternov effect (radiative)

Radiative polarization

\[ W_{\sigma}^{\uparrow\downarrow} = W_{\sigma}^{-1} \left\{ \frac{7}{8} - \xi \left( \frac{25\sqrt{3}}{12} - \zeta \right) + \xi^2 \left( \frac{335}{18} + \frac{245\sqrt{3}}{48} - \zeta \right) + \cdots \right\}, \]

\[ W_{\sigma}^{\uparrow\downarrow} = W_{\sigma}^{-1} \frac{\xi^2}{18}, \]

\[ W_{\pi}^{\uparrow\downarrow} = W_{\pi}^{-1} \left\{ \frac{1}{8} - \xi \left( \frac{5\sqrt{3}}{24} + \xi^2 \frac{25}{18} + \cdots \right) \right\}, \]

\[ W_{\pi}^{\uparrow\downarrow} = W_{\pi}^{-1} \frac{\xi^2}{18} \left\{ 1 + \xi \frac{105\sqrt{3}}{184} \right\}. \]

\[ P_{\text{eq}} = \frac{N_+ - N_-}{N_+ + N_-} = \frac{p_+ - p_-}{p_+ + p_-} \]

\[ P(t) = P_{\text{ST}} (1 - e^{-t/\tau_{\text{pol}}}) \]


\[ \tau_{\text{pol}}(s) \approx 3654 \frac{(R/\rho)}{[B(T)]^3[E(\text{GeV})]^2} \]

\[ P_{\text{ST}} = \frac{8}{5\sqrt{3}} \approx 92.376\% \]

Schematic layout of VEPP-2M complex.
Spin dynamics in strong laser field

Non-linear Compton Scattering

The radiation probability is dependent on the spin states [2]

\[
\frac{dP}{d\delta d\tau} = -\frac{\alpha}{2b} \left[ 2A_1(z) + g \frac{4A_1'(z)}{z} + s\zeta 2t \frac{A(z)}{\sqrt{z}} \right]
\]

- Spin parallel or anti-parallel to the B-field
- No S-T effect
- Loss of information


Generalized Sokolov-Ternov theory

Generalized S-T

- Define the transition probability along a complete and orthogonal axis

\[ A = P_{\uparrow\uparrow}, \quad B = P_{\uparrow\downarrow} \]

- Build up Polarization along \( \zeta, \eta, \kappa \) from spin flip rates

\[ P(t) = \frac{A-B}{A+B} \left[ 1 - \exp \left( -\frac{t}{\tau} \right) \right] + P_0 \exp \left( -\frac{t}{\tau} \right) \]

Generalized Sokolov-Ternov theory

Transverse polarization
Reproduced the S-T effect
(spin is parallel/antiparallel to the B-field)

Longitudinal polarization
Avoid information loss
(spin is perpendicular to the B-field)
Spin-dependent deflection in the SFQED regime
Spin effects manifestation in radiation-reaction

- The radiation-reaction effect:
  electron loses energy due to photon emission
- The spin effect:
  Spin anti-parallel radiates more energies than parallel.

Symmetry is broken when both effects are coupled to each other.
A net momentum shift is induced along the $s \times k$ direction.
quantum field theory
(including Sokolov Ternov)

radiation reaction

classical field theory

T-BMT

SG force

quantum field theory

radiation

trajectory

spin

High Power Laser Science and Engineering 8 (2020)
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**Storage rings: The Sokoly-Ternov effect**

**Radiative polarization**

\[ W_{\sigma}^{\uparrow \downarrow} = W_{\sigma}^{\text{cl}} \left\{ \frac{7}{8} - \xi \left( \frac{25 \sqrt{3}}{12} - \zeta \right) + \xi^2 \left( \frac{335}{18} + \frac{245 \sqrt{3}}{48} \zeta \right) + \cdots \right\}, \]

\[ W_{\sigma}^{\uparrow} = W_{\sigma}^{\text{cl}} \frac{\xi^2}{18}, \]

\[ W_{\pi}^{\uparrow \downarrow} = W_{\pi}^{\text{cl}} \left\{ \frac{1}{8} - \xi \frac{5 \sqrt{3}}{24} + \xi^2 \frac{25}{18} \frac{105 \sqrt{3}}{184} + \cdots \right\}, \]

\[ W_{\pi}^{\uparrow} = W_{\pi}^{\text{cl}} \xi^2 \frac{23}{18} \left\{ 1 + \xi \frac{105 \sqrt{3}}{184} \right\}. \]

\[ P_{\text{eq}} = \frac{N_{+} - N_{-}}{N_{+} + N_{-}} = \frac{p_{+} - p_{-}}{p_{+} + p_{-}} \]

\[ P(t) = P_{\text{ST}} \left( 1 - e^{-t/\tau_{\text{pol}}} \right) \]

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Laser acceleration: High acceleration gradient

Conventional Accelerator (1km)
(10⁷⁻⁸V/m)

LHC, Higgs Boson, Nobel Prize (2013)

Radiofrequency cavity (1 m-long)

Laser Acceleration (1cm)
(10¹²V/m)

W. Mori & L.O. Silva

\[ E_c = \frac{m_e c \omega_p}{e} \approx 300 \text{GV/m} \quad (\text{for } n_e=10^{19} \text{ cm}^{-3}) \]
Is it possible to generate polarized electron in laser-driven wakefield acceleration?
Accelerate and then polarize in Storage rings due to Sokolov-Ternov Effect


Extract from polarized atoms/photocathodes and accelerate in Linacs


Spin filters & Beam splitters


\[
T_{\text{pol, electron}}^{-1} = \frac{5\sqrt{3}}{8} \frac{e^5 F^3 \gamma_e^2}{\hbar m_e^5 c^8}
\]

For typical LWFA

\( \gamma_e \sim 10^3 \) and \( F \sim 10^{16} \text{V/m} \).

One finds \( T_{\text{pol, S-T}} \sim 1 \mu s \)

>> acceleration duration (\( \sim \) ns scale)

Accelerate and then polarize in Storage rings due to Sokolov-Ternov Effect


Extract from polarized atoms/photocathodes and accelerate in Linacs


Spin filters & Beam splitters


|$F_{SG}/F_L| \sim |\nabla (S\cdot B)/\gamma_e^2 c B m_e| \sim h/\lambda m_e c \gamma_e^2 \ll 1$

The Stern-Gerlach Force is negligible compared to laser-plasma fields

PRST-AB, in preparation

Colliding a 10 PW laser with multi-GeV electrons to split electrons of different spin states (spin-flip rates depending on the states)
How to prepare a 100% polarized electron target?

Is it possible to preserve the beam polarization during LWFA?

100% pre-polarized electron target is feasible

Pre-polarization + LWFA
Particle spin in PIC simulations

\[
\begin{align*}
\frac{ds^n}{dt} &= \frac{ds^n}{dt} = -\Omega^n \times s^n = -\Omega^n \times s^n \\
\frac{d}{dt} &= -\Omega^n \times s^n \\
|\Omega^n| &= \begin{vmatrix} \Omega^n & s^n \\ \Omega^n & \Omega^n \end{vmatrix}, s^n = s^n - s^n \\
|\Omega^n| &= -\Omega^n \times s^n \\
\begin{vmatrix} \Omega^n & |\Omega^n| \end{vmatrix} &= \begin{vmatrix} \Omega^n & |\Omega^n| \end{vmatrix} \\
\theta^n &= |\Omega^n| \Delta t \\
s_{\perp}^{n+1} &= s_{\perp}^n \cos(\theta^n) + r^n \sin(\theta^n) \\
s^n_{\perp} &= s_{\perp}^{n+1} + s^n_{\parallel}
\end{align*}
\]
Polarization in LWFA

Stage I: Laser-electron interaction
Stage II: Injection (depolarization)
Stage III: Acceleration

$8.6 \times 10^{18} \text{ W/cm}^2$, 21.4 fs, 10 um, $n_0=10^{18} \text{ cm}^{-3}$
Depolarization: self-generated fields

Spin precession frequency

\[ \Omega = \frac{e}{m} \left( \frac{B}{\gamma} - \frac{1}{\gamma + 1} \frac{\nu}{c^2} \times E \right) + a_e \frac{e}{m} \left( B - \frac{\gamma}{\gamma + 1} \frac{\nu}{c^2} (\nu \cdot B) - \frac{\nu}{c^2} \times E \right) \]

where \( B \sim B_{\phi}, E_r \sim -B_{\phi} \)

\[ \Omega \approx eB_{\phi}(2 + \beta_x)/2me_{\phi} \]

Azimuthal B-field

Current density

\( a_e = (g - 2)/2 \approx 1.16 \times 10^{-3} \)
Strong restriction on beam flux to preserve polarization

\[ P \approx 0.5 + \frac{1}{2} \int_0^\infty \cos[\pi e n_p c a r^2] \, dr^2 / \Delta r^2 \approx \frac{1 + \text{sinc}(\alpha I_{\text{peak}})}{2} \]

80% polarization

Preserving the beam polarization imposes strong restriction on the loaded beam charge / flux

\[ I_{\text{peak}} < 2.2 \text{kA} \]
Preserving polarization: new geometry?
Vortex LWFA: high beam charge but low current density

- Peak current density and B-field are $1/3$ of the Gaussian beam driver.
- The region of magnetic field is significantly reduced.
Vortex LWFA preserves the beam polarization at very high beam charge/flux

10* enhancement at 80% polarization

Physical Review E 100, 043202 (2019)
- Spin precession is dependent on the azimuthal angle
- Precession is significantly suppressed when spin is parallel/anti-parallel to the magnetic field
Due to the symmetric bubble structure, the azimuthal angle is locked with the angle where electrons are emitted.

High polarization purity observed at certain angles

Spin filter is possible by identifying electrons located in certain azimuthal angle region

An X-shaped spin filter purifies electron polarization at any injected beam charge.

Electron-positron collider
Towards the high energy frontier

Multi-staged LWFA or PWFA towards 100 GeV

High beam polarization for e-e^{+} collider
High energy polarized particle beam

Particle physics, nuclear physics and material science

<table>
<thead>
<tr>
<th>Institution</th>
<th>Location</th>
<th>Machine</th>
<th>Acronym</th>
</tr>
</thead>
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<tr>
<td>ANL</td>
<td>Argonne, IL, USA</td>
<td>ZGS</td>
<td>Zero Gradient Synchrotron</td>
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<tr>
<td>Berlin</td>
<td>Berlin, Germany</td>
<td>BESSY-I, II</td>
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<td>BINP</td>
<td>Novosibirsk, Russia</td>
<td>VEPP-(2, 2M, 3, 4)</td>
<td>Colliding Electron–Positron Beams</td>
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<tr>
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<td>Large Electron–Positron Project</td>
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<td>KEK-B</td>
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<td>KEK Proton Synchrotron</td>
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<td>(Tri-Ring Intersecting Storage Accelerators at Nippon)</td>
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<td>Amsterdam Pulse stretcher</td>
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<td>Newport News, VA, USA</td>
<td>CEBAF</td>
<td>Continuous Electron Beam Accelerator Facility</td>
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Preparing 100% pre-polarized electron target

100 mJ @ 1064 nm
Alignment of HCl bonds

20 mJ @ 213 nm
Photo-dissociation and polarization of the H nucleus

300 J @ 800 nm
Acceleration of the protons in gas jet
Conclusions

- The world-leading 10-100PW laser facilities (SULF and SEL) in China take strong-field QED research as one of the major science cases.

- Spin is a new degree of freedom manifesting the essence of strong-field QED.

- Laser-driven wakefield acceleration is promising in providing compact polarized particle sources.
Thank you for your attention!