Laser-Plasma Interactions in Magnetized Environment

Yuan Shi

Princeton Plasma Physics Laboratory
Department of Astrophysical Sciences
Princeton University

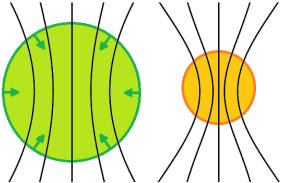
Invited Talk, 59th APS DPP
October 23, 2017

Acknowledgment

- Ph.D. Advidors : Nathaniel J. Fisch and Hong Qin
- Collaborator : Qing Jia
- Discussions : Ilya Y. Dodin, Daniel E. Ruiz, and Jian Zheng
- Funding : NNSA Grant No. DE-NA0002948
  AFOSR Grant No. FA9550-15-1-0391
  DOE Grant No. DEAC02-09CH11466

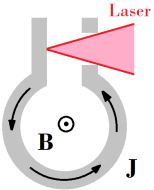
Why Magnetized? Strong Magnetic Fields Become Available

Flux Compression



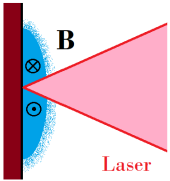
- $B \sim 10$ MG
- Seed fields compressed by imploding targets
- New phenomena?

Capacitor-Coil



- $B \sim 10$ MG
- Technology for large currents/strong fields
- New applications?

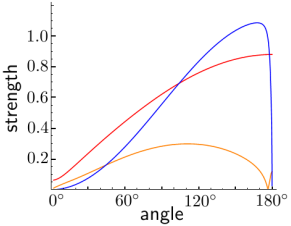
Surface Current



- $B \sim 1$ GG
- B-field generated near ablated surfaces
- New regimes?

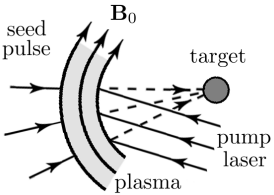
New Challenges/Opportunities With Strong Fields

New Phenomena



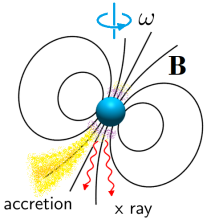
- Laser scattering due to magnetized resonances
- Coherent scattering enhanced/suppressed at special angle/frequency

New Applications



- Pulse compression improved by B-fields
- Expand operation window to higher frequency/intensity

New Regimes

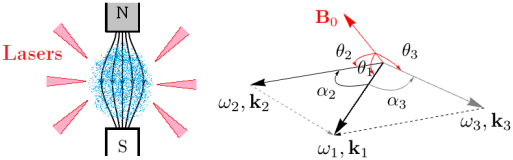


- Relativistic-quantum regime near x-ray pulsars
- Simulate pulsar magnetosphere in future experiments?

Outline

Scattering Anisotropic in Magnetized Plasmas (PRE **96**, 023204)

- Multiple lasers exchange energy via magnetic resonances in implosions



- How much collective scattering? Simplest case: resonant triplets

$$\mathbf{k}_1 = \mathbf{k}_2 + \mathbf{k}_3$$
$$\omega_1 = \omega_2 + \omega_3$$

Classical Baseline: Cold Fluids

$$\partial_t n_s = -\nabla \cdot (n_s \mathbf{v}_s)$$
$$\partial_t \mathbf{v}_s = -\mathbf{v}_s \cdot \nabla \mathbf{v}_s + \frac{e_s}{m_s}(\mathbf{E} + \mathbf{v}_s \times \overbrace{\mathbf{B}}^{\mathbf{B}_0+\tilde{\mathbf{B}}})$$
$$\partial_t \mathbf{B} = -\nabla \times \mathbf{E}$$
$$\partial_t \mathbf{E} = c^2 \nabla \times \mathbf{B} - \frac{1}{\epsilon_0} \sum e_s n_s \mathbf{v}_s$$

Perturbative Solution to 2nd Order

$$\sum_{\mathbf{k}\in\mathbb{K}_2} \overbrace{\mathbb{D}_{\mathbf{k}} \mathcal{E}^{(2)}_{\mathbf{k}}}^{\text{Quasimodes}} e^{i\theta_{\mathbf{k}}} + i \sum_{\mathbf{k}\in\mathbb{K}_1} \overbrace{\omega_{\mathbf{k}} \mathbb{H}_{\mathbf{k}} d^{\mathbf{k}}_{t(1)} \mathcal{E}^{(1)}_{\mathbf{k}}}^{\text{Envelop Advection}} e^{i\theta_{\mathbf{k}}}$$
$$= \frac{i}{2} \sum_{s,\mathbf{q},\mathbf{q}'\in\mathbb{K}_1} e^{i(\theta_{\mathbf{q}}+\theta_{\mathbf{q}'})} \mathbf{S}^s_{\mathbf{q},\mathbf{q}'} \leftarrow \textbf{Scattering}$$

Solution to Fluid Equations ⇒ Reduced Model for Laser Scattering

Three-Waves Envelop Equations

$$
\begin{aligned}
d_t^{\mathbf{k}_1} a_1 &= -\frac{\Gamma}{\omega_1} a_2 a_3 \\
d_t^{\mathbf{k}_2} a_2 &= \frac{\Gamma}{\omega_2} a_3 a_1 \\
d_t^{\mathbf{k}_3} a_3 &= \frac{\Gamma}{\omega_3} a_1 a_2
\end{aligned}
$$

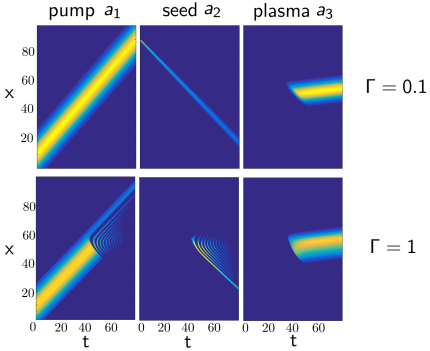
Coupling Coefficient Γ

We obtain simple formula for Γ in the most general geometry with $\mathbf{B}_0$

$$
\Gamma = \sum_s \frac{Z_s \omega_{ps}^2 \Theta_r^s}{4 M_s (u_1 u_2 u_3)^{1/2}}
$$

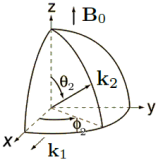
Why Coupling Coefficient Important?

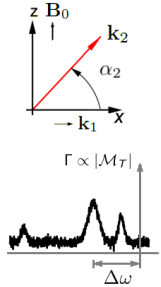
- Determined evolution of pulses
- Example: backscattering of lasers

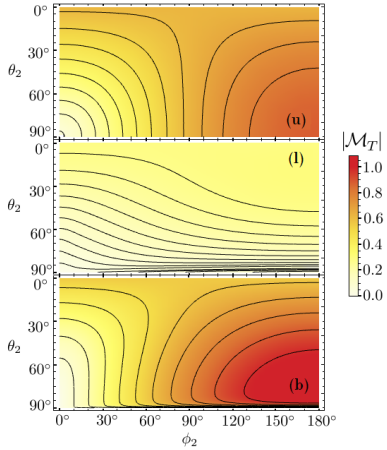


Key Parameter in Reduced Model: Coupling Coefficient

Example: Perpendicular Pump Laser

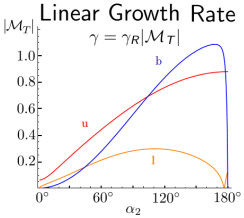


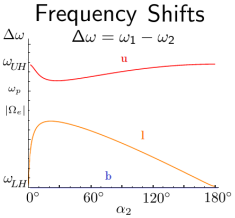




Angle-Dependent Scattering Strength

- Upper-hybrid-like waves (u) favor exact backscattering, k_3 effect dominants
- Lower-hybrid-like waves (l) favor $\perp$ scattering, e^- and i^+ scatterings exact cancel at special angles
- Alfvén-like waves (b) favor backward, but suppress exact backscattering





Application: Laser Pulse Compression (PRE **95**, 023211)

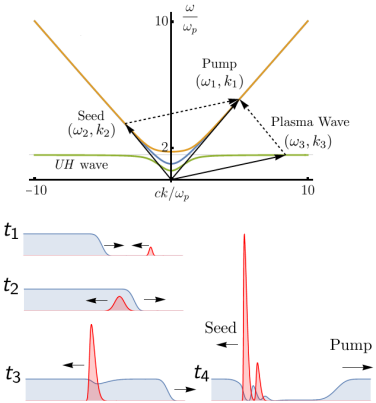
Limitations of Existing Techniques

- Chirped Pulse Amplification:
  Works in optical regime ~ 1 eV
  Unfocused intensity $\sim 10^{14}\mathrm{W/cm}^2$
- Raman/Brillouin Compressions:
  Vulnerable to density fluctuations
  Frequency up to soft x-ray ~ 100 eV
  Unfocused intensity $\lesssim 10^{18}\mathrm{W/cm}^2$

Magnetized Pulse Compression

- Mediated by magnetized resonances
- Less sensitive to density fluctuations
- Works for higher frequency/intensity

Example: Upper-Hybrid Mediation

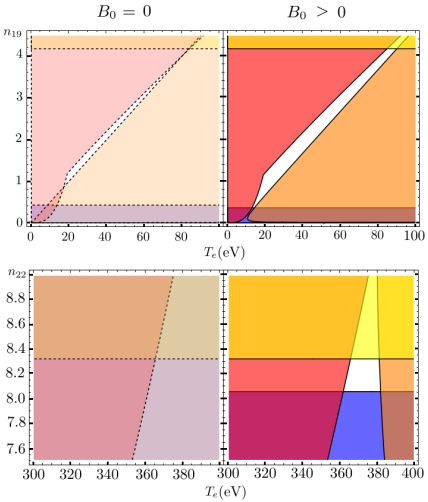


Magnetic Fields Relax Limiting Effects

Limiting Effects

- Instabilities: phase mixing, modulational filiamentation instability, wakefield
- Damping: collisional, collisionless
- Engineering: plasma density non-uniformity

⇒ Pulse compression only operable in T-n window

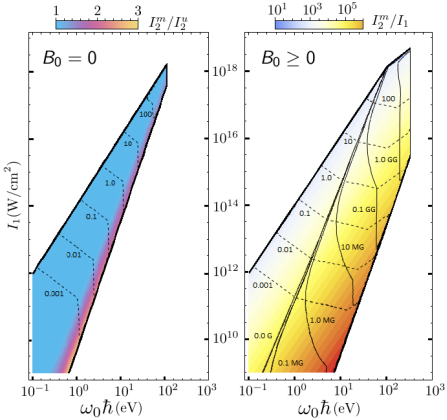


Compress KrF
$I_1 = 10^{13}$ W/cm^2
$\omega_0\hbar = 5$ eV
$B_0 = 5$ MG

Compress x-ray
$I_1 = 10^{18}$ W/cm^2
$\omega_0\hbar = 250$ eV
$B_0 = 1.5$ GG

Magnetic Fields Improve Pulse Compression

Pump Laser Parameter Space



Expand Range of Applicability

- Enable compressing pump lasers of higher frequency ⇐ Reduced damping
- Enable amplification of seed pulses to higher intensity ⇐ Reduced instability

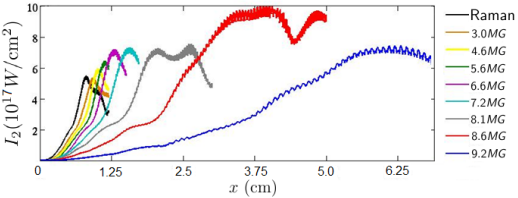
Increase Engineering Flexibility

- Higher controllability: external magnetic fields easier to control than internal plasma density
- Further optimization: extra degree of freedom, select fraction of density to be replaced by magnetic fields

Numeric Validations Using 1D PIC (PoP **24**, 093103. Qing Jia Poster: PP11.00007)

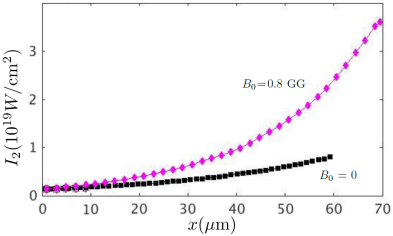
Optical Regime: 1 μm Laser

- Scan magnetic field, fixed ω_3
  Pump: 1.0μm, $I_{10} = 3.5 \times 10^{14}$W/cm^2
  Seed : 1.1μm, $I_{20} = 1.8 \times 10^{13}$W/cm^2
- Slower growth, longer amplification
  $\Rightarrow$ Higher output intensity



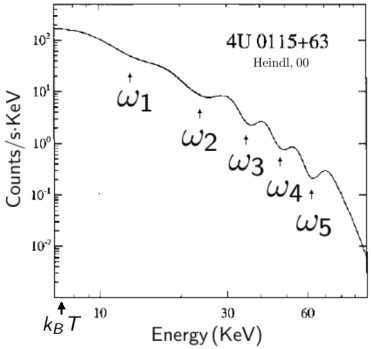
X-Ray Regime: 10 nm Laser

- Scan magnetic field, fixed ω_3
  Pump: 10 nm, $I_{10} = 1.4 \times 10^{18}$W/cm^2
  Seed : 11 nm, $I_{20} = 1.4 \times 10^{18}$W/cm^2
- Slower growth rate, smaller damping
  $\Rightarrow$ Faster effective growth



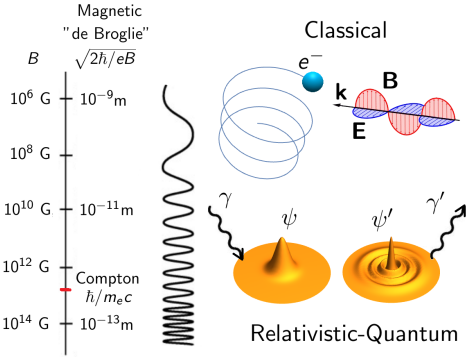
Relativistic-Quantum Regime $\Leftarrow$ Strong Fields

Example: X-Ray Pulsars $B \sim 10^{12}$ G



- Cyclotron absorptions $\hbar\Omega_e > k_B T$
- Anharmonic $\Leftarrow$ Relativistic shifts

- Relativistic important: $\mathcal{E} \gtrsim m_e c^2$
- Quantum important: $\epsilon_* \gtrsim k_B T, U_p$



New Physics in Old Problem: Wave Propagation (PRA **94**, 012124)

How We Compute RQ Effects?

- Toy Model: Scalar-QED Plasma

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \quad \leftarrow \text{EM Fields}$$
$$+ \underbrace{(D_\mu\phi)^*(D^\mu\phi) - m^2\phi^*\phi}_{\text{Charged Bosons}}$$

- Wave effective action $\Leftarrow$ path integral

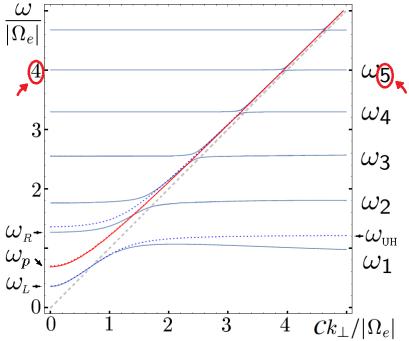
$$\Gamma = \underbrace{-\frac{1}{4}\mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu}}_{\text{Vacuum}} + \underbrace{\mathcal{A}_\mu\Sigma_2^{\mu\nu}\mathcal{A}_\nu}_{\text{Linear Response}} + o(e^2)$$

$$\Sigma_2^{\mu\nu} = \Sigma_{2,\text{bk}}^{\mu\nu} + \Sigma_{2,\text{vac}}^{\mu\nu}$$

- Response tensors $\Leftarrow$ Feynman rules

Wave Dispersion Relation Modified

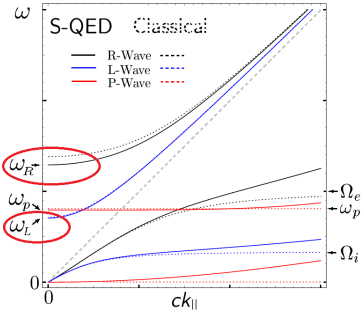
- Propagation $\perp$ $\mathbf{B}_0$ in cold e^- gas
- Resonance ω_5 can appear at $4\Omega_e$



Relativistic-Quantum Effects Observable in Experiments?

Modifications Magnified Near Cutoffs

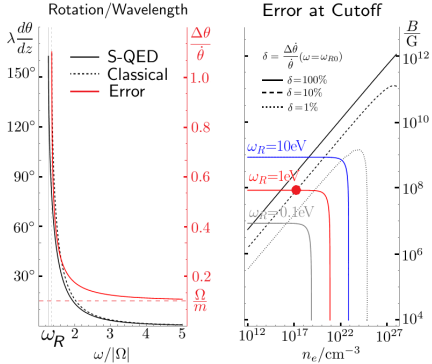
- Propagation $\parallel \mathbf{B}_0$ in e-i plasma
- R-cutoff shifted more than L-cutoff



Example: $\frac{\omega_{pe}}{\Omega_e} = 0.7$, $\frac{\Omega_e \hbar}{m_e c^2} = 0.1$, $\frac{m_i}{m_e} = 3$

Corrections to Faraday Rotation

- Different dependence on ω
- Large error for strong B small n_e



Summary: What We Already Know

- Laser Scattering: New Phenomena
  - Scattering is anisotropic due to magnetic fields
  - Scattering is enhanced/suppressed at special angles

  $\Rightarrow$ Possible to arrange beam geometry to optimize laser-plasma coupling
- Laser Amplification: New Applications
  - Magnetic resonances mediate pulse compression
  - Magnetized mediations require less density, reduce instability/damping

  $\Rightarrow$ Possible to compress higher frequency pumps, producing more intense pulses
- Laser Propagation: New Regimes
  - Dispersion relation modified by relativistic quantum effects
  - Corrections to Faraday rotation and cyclotron resonances in strong fields

  $\Rightarrow$ Possible to extract pulsar magnetosphere profiles from x-ray spectra?

Open Questions: What's Next?

Theory

- Spin, thermal, inhomogeneity, higher-order effects
- Retrieval plasma profile from spectra of x-ray pulsar

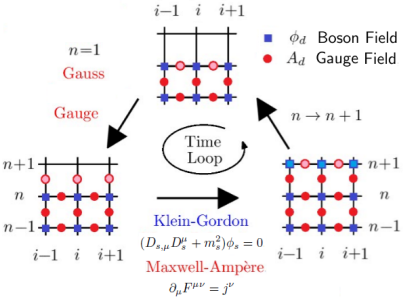
Simulation

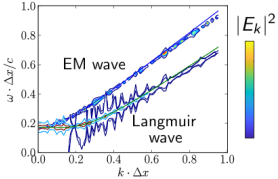
- Reduced model for laser scattering
- Faithful collision module for PIC
- Schemes for simulating relativistic quantum plasmas in strong fields (e.g. lattice-QED)

Experiments

- Measure Faraday rotation, UV/X-ray transmission
- Compare spectral retrieval with measurements
- Demonstrate magnetized pulse compressions

. . . . . .





References

U. Wagner, M. Tatarakis, A. Gopal, F. N. Beg *et al.*, Phys. Rev. E **70**, 026401 (2004).

O. V. Gotchev, P.Y. Chang, J. P. Knauer, D. D. Meyerhofer *et al.*, Phys. Rev. Lett. **103**, 215004 (2009).

V. T. Tikhonchuk, M. Bailly-Grandvaux, J. J. Santos, and A. Poy, Phys. Rev. E **96**, 023202 (2017).

V. M. Malkin, G. Shvets, and N. J. Fisch, Phys. Rev. Lett. 82, 4448 (1999).

Y. Shi, N. J. Fisch, and H. Qin, Phys. Rev. A **94**, 012124 (2016).

Y. Shi, H. Qin, and N. J. Fisch, Phys. Rev. E **95**, 023211 (2017).

Y. Shi, H. Qin, and N. J. Fisch, Phys. Rev. E **96**, 023204 (2017).

Q. Jia, Y. Shi, H. Qin, and N. J. Fisch, Phys. Plasmas **24**, 093103 (2017).

W. A. Heindl, W. Coburn, D. E. Gruber *et al.*, AIP Conf. Proc. **510**, 173 (2000).

Questions/Comments/Collaborations Welcome!

Relativistic-Quantum Regime: Energy Scales

Energy Scales of Plasma

- Thermal energy $k_B T$
- Fermi energy ϵ_F
- Plasmon energy $\epsilon_p = \omega_p \hbar$
- Gyro energy $\epsilon_g = \Omega \hbar$

Energy Scales of Fields

- Electric field energy $\epsilon_E = \sqrt{eEc\hbar}$
- Magnetic field energy $\epsilon_B = \sqrt{eBc^2\hbar}$
- Photon energy $\epsilon_\gamma = \omega_\gamma \hbar$
- Ponderomotive energy U_p

- Relativistic effects important when

$$\mathcal{E} \gtrsim m_e c^2$$

where $\mathcal{E}$ is any energy scale of plasma or field.

- Quantum effects important when

$$\epsilon_* \gtrsim k_B T, U_p$$

where ϵ_* is any nonthermal energy scale of plasma or field.

- Example: in pulsar magnetosphere, both relativistic and quantum effects important $\Rightarrow$ Need new theory

Model Relativistic Quantum Plasmas: Quantum Electrodynamics

- Toy model: scalar-QED for spin-0 bosonic plasmas couple to EM fields

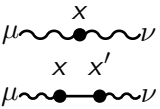
$$\begin{aligned}\mathcal{L} &= -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \qquad \leftarrow \text{EM Fields} \\ &+ \underbrace{(D_\mu\phi)^*(D^\mu\phi) - m^2\phi^*\phi}_{\text{Charged Bosons}}\end{aligned}$$

- Wave effective action $\Leftarrow$ path integral

$$\Gamma = \underbrace{-\frac{1}{4}\mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu}}_{\text{Vacuum}} + \underbrace{\mathcal{A}_\mu\Sigma_2^{\mu\nu}\mathcal{A}_\nu}_{\substack{\text{Linear Response} \\ \Sigma_2^{\mu\nu}=\Sigma_{2,\text{bk}}^{\mu\nu}+\Sigma_{2,\text{vac}}^{\mu\nu}}} + o(e^2)$$

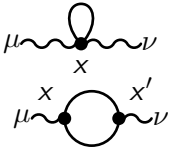
- Response tensors $\Leftarrow$ Feynman rules
- Background plasma response

$$\Sigma_{2,bk}^{\mu\nu}(x,x') =$$



- Vacuum polarization response

$$\Sigma_{2,vac}^{\mu\nu}(x,x') =$$



Key Parameter in Reduced Model: Coupling Coefficient

Angular Dependence

- Coupling coefficient between two transverse lasers

$$\Gamma_T = \sum_s \frac{Z_s \omega_{ps}^2}{4M_s} \frac{ck_3}{\omega_3} \frac{\hat{\mathbf{k}}_3 \cdot \mathbb{F}_{s,3} \hat{\mathbf{k}}_3}{u_3^{1/2}}$$

- Scattering mediated by magnetized plasma resonance $(\omega_3, \mathbf{k}_3)$

$$\hat{\mathbf{k}}_3 \cdot \mathbb{F}_{s,3} \hat{\mathbf{k}}_3 = \gamma_{s,3}^2 (1 - \beta_{s,3}^2 \cos^2 \theta_3)$$

$$u_3 = 1 + \sum_s \frac{\omega_{ps}^2}{\omega_3^2} \gamma_{s,3}^4 \beta_{s,3}^2 \sin^2 \theta_3$$

Example: Parallel Pump Laser

- Cyclotron waves enhance $\perp$ suppress $\|$