Thermoelectric-induced electric field in magnetized and evolving quark-gluon plasma

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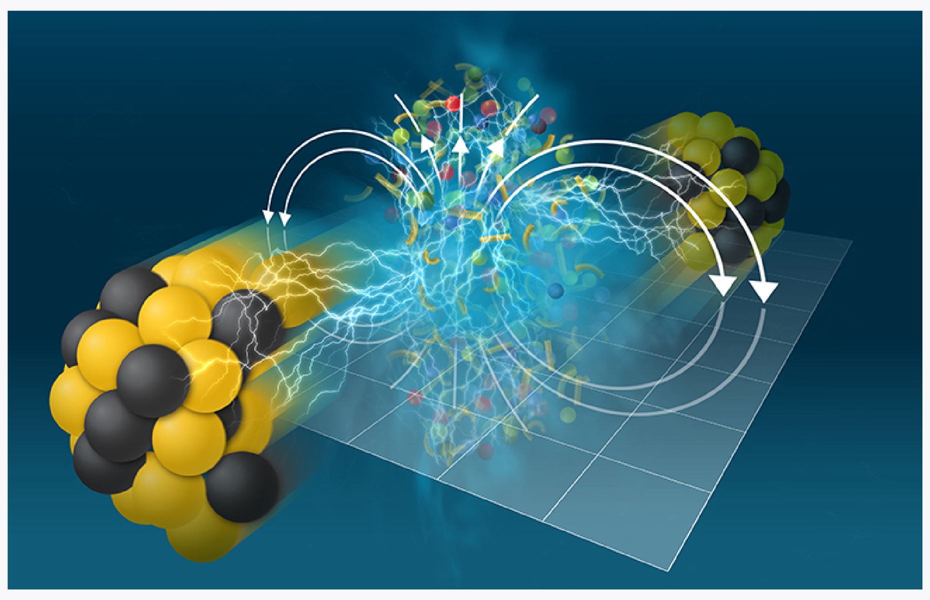
1. Introduction

- Quark-gluon plasma (QGP), created in relativistic heavy-ion collisions, is a locally thermalized medium with electrically charged quarks that exhibit thermoelectric properties during its evolution, hence it induces a local electromagnetic (EM) field
- Even in head-on collisions, this phenomenon can produce an EM field, while additionally in peripheral collisions, spectator currents create a transient magnetic field ($\sim 10^{18} - 10^{19}$ G) that disturbs the isotropy of the induced field



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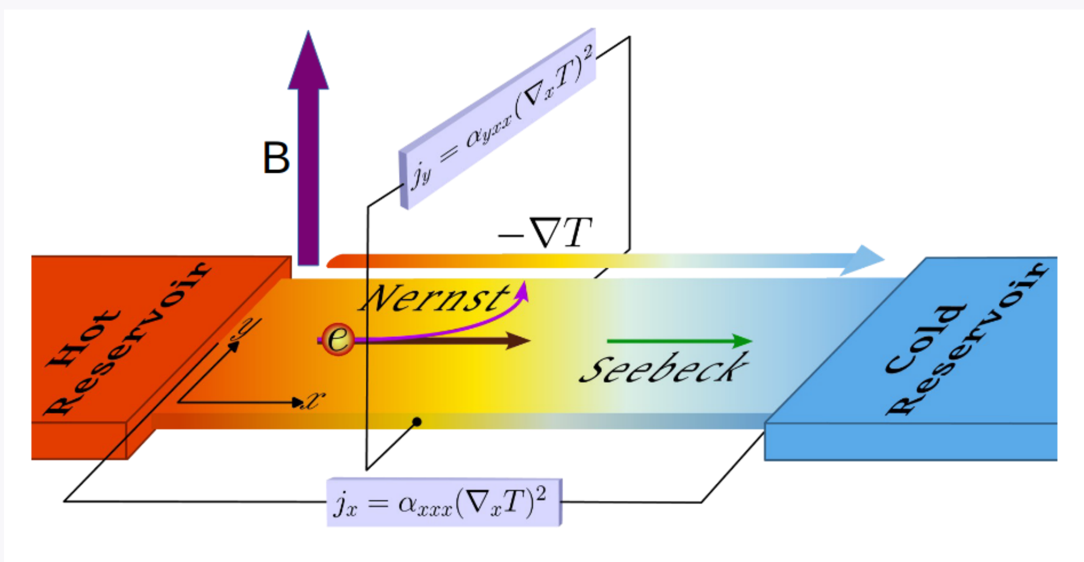
Using the Gubser hydrodynamic flow for cooling rates and a quasiparticle-based model with lattice quantum chromodynamics equations of state, the study estimates the induced electric field (a maximum value of $eE \approx 1\ m_\pi^2$) and highlights the crucial role of thermoelectric coefficients such as Seebeck, magneto-Seebeck, and Nernst coefficients.

2. Quasiparticle model

We use a quasiparticle model formulated by Gorenstein and Yang [1] for the numerical estimation. It is a phenomenological model where the lattice QCD equation of state for QGP is achieved by considering the thermal masses of the partons. The *thermal mass $m(T)$* arises from the interactions among the partons.

3. Thermoelectric effect

The thermoelectric effect refers to the direct conversion of temperature differences into electrical voltage and vice versa. The *Seebeck coefficient (S)* quantifies the voltage generated per unit temperature difference in a thermoelectric material. The presence of a magnetic field leads to the production of transverse voltage in the system.



4. Formalism

In the presence of an electromagnetic field, the general form of *electric current density and heat current* can be expressed as $\vec{j} = j_e\hat{e} + j_H(\hat{e}\times\hat{b})$, and $\vec{I} = \kappa_0\vec{\nabla}T + \kappa_H(\vec{\nabla}T\times\hat{b})$. j_e is the Ohmic-like component, and j_H the Hall-like components of the total current.

The total single-particle distribution function (f_i) for a system slightly out of equilibrium (δf_i) can be written as $f_i = f_i^0 + \delta f_i$. To find the expression of δf_i in the presence of an external electromagnetic field, we solve the Boltzmann transport equation ***(BTE)*** with the help of relaxation time approximation ***(RTA)*** as [2]

$$\frac{\partial f_i}{\partial t} + \frac{\vec{k_i}}{\omega_i}\cdot\frac{\partial f_i}{\partial \vec{x}} + q_i\left(\vec{E} + \frac{\vec{k_i}}{\omega_i}\times\vec{B}\right)\cdot\frac{\partial f_i}{\partial \vec{k_i}} = -\frac{\delta f_i}{\tau_R^i}, \qquad (1)$$

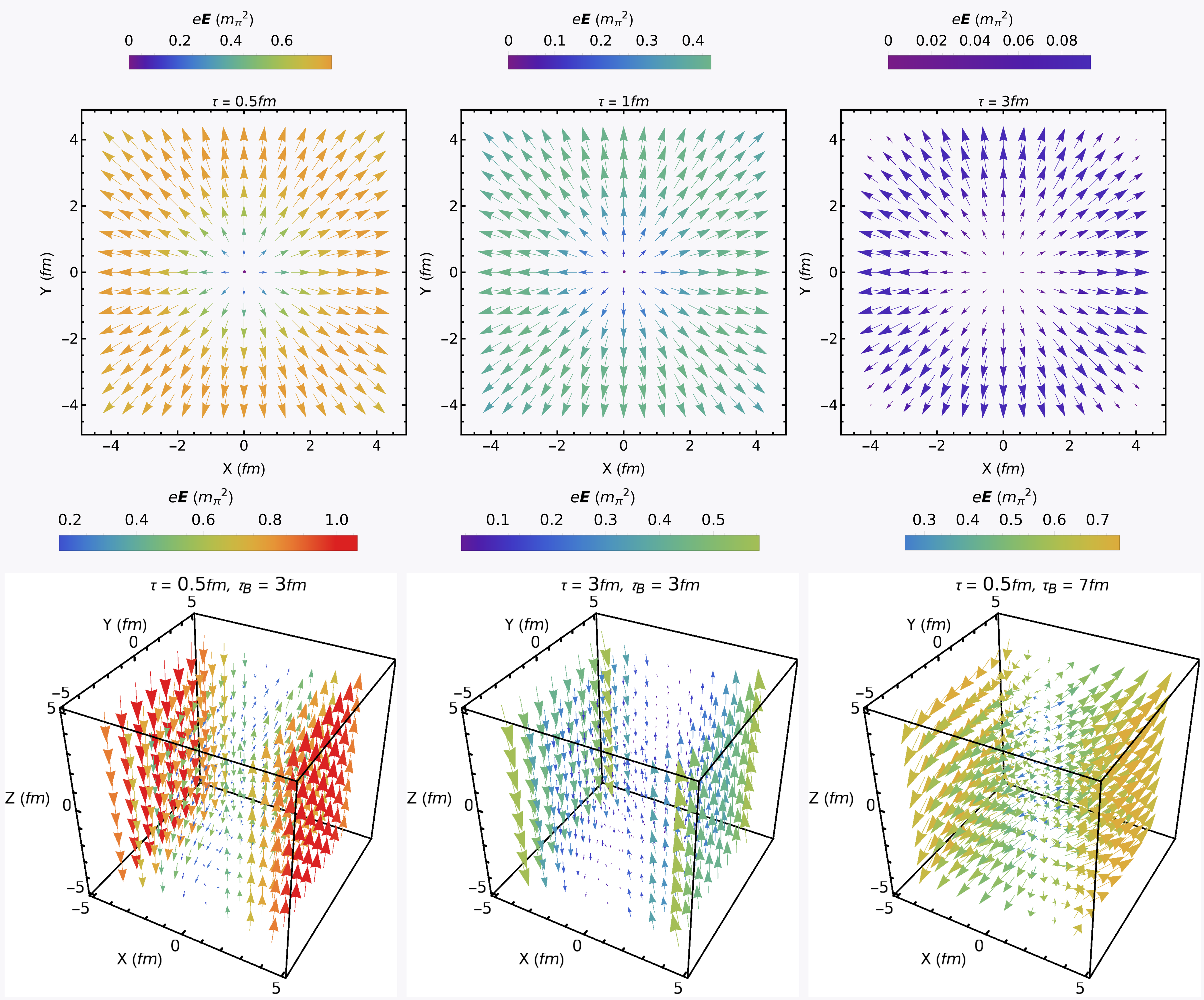
where τ_R^i is the relaxation time of the particle. We have to assume an ansatz of $\delta f_i = (\vec{k_i}\cdot\vec{\Omega}_\sigma)\frac{\partial f_i^0}{\partial\omega}$ and a general form can be assumed as $\vec{\Omega}_\sigma = \alpha_1\vec{E} + \alpha_2\dot{\vec{E}} + \alpha_3\vec{\nabla}T + \alpha_4\vec{\nabla}\dot{T} + \alpha_5(\vec{\nabla}T\times\vec{B}) + \alpha_6(\vec{\nabla}T\times\dot{\vec{B}}) + \alpha_7(\vec{\nabla}\dot{T}\times\vec{B}) + \alpha_8(\vec{E}\times\vec{B}) + \alpha_9(\vec{E}\times\dot{\vec{B}}) + \alpha_{10}(\dot{\vec{E}}\times\vec{B})$. ***For more details, one can check the Ref. [3].*** ***The components of the electric current in the three spatial directions are given as:***

$$\mathrm{j}^x = \sum_i \frac{q_i g_i}{3}\int\frac{d^3|\vec{k_i}|}{(2\pi)^3}v_i^2\frac{\tau_R^i q_i}{(1+\chi_i+\chi_i^2)(1+\chi_i)}\left\{\left(\frac{(1+\chi_i^2)+\chi_i(2+\chi_i)}{(1+\chi_i^2)}\right)E^x \pm \chi\left(\frac{(1+\chi_i^2)(1+\chi_i)+\chi_i(2+\chi_i)}{(1+\chi_i^2)}\right)(E^z - E^y)\right\}\left(-\frac{\partial f_i^0}{\partial\omega_i}\right) + \sum_i\frac{q_i g_i}{3}\int\frac{d^3|\vec{k_i}|}{(2\pi)^3}v_i^2\frac{\tau_R^i(\omega_i - \mathrm{b}_i h)}{T(1+\chi_i+\chi_i^2)(1+\chi_i)}\left\{(1+\chi_i)\frac{\partial T}{\partial x} - \tau_R^i\frac{(1+\chi_i-\chi_i^2)}{(1+\chi_i^2)}\frac{\partial\dot{T}}{\partial x} \pm \chi_i(1+\chi_i)\left(\frac{\partial T}{\partial z} - \frac{\partial T}{\partial y}\right) \mp \tau_R^i\frac{\chi_i(2+\chi_i)}{(1+\chi_i^2)}\left(\frac{\partial\dot{T}}{\partial z} - \frac{\partial\dot{T}}{\partial y}\right)\right\}\frac{\partial f_i^0}{\partial\omega_i}.$$

Here, b_i is the baryon quantum number of i^{th} species. h is enthalpy per baryon number, and $\chi_i = \frac{\tau_R^i}{\tau_B} = \frac{\tau_R^i}{\tau_E}$. The components j^y and j^z can be obtained from the above equation by changing x, y, and z in cyclic order. Now, ***by setting $j_x = j_y = j_z = 0$, i.e., when net current due to the external field is zero***, we get

$$\mathrm{E}_x = \frac{\left\{\sigma_e L_{34} + \sigma_H L_{56}\right\}\frac{dT}{dx}}{T\left\{(\sigma_e)^2 + (\sigma_H)^2\right\}} + \frac{\left\{\sigma_e L_{56} - \sigma_H L_{34}\right\}\frac{dT}{dz}}{T\left\{(\sigma_e)^2 + (\sigma_H)^2\right\}},\quad E_y = \frac{L_{34}}{T\sigma_e}\frac{dT}{dy},\quad E_z = \frac{\left\{\sigma_H L_{34} - \sigma_e L_{56}\right\}\frac{dT}{dx}}{T\left\{(\sigma_e)^2 + (\sigma_H)^2\right\}} + \frac{\left\{\sigma_e L_{34} + \sigma_H L_{56}\right\}\frac{dT}{dz}}{T\left\{(\sigma_e)^2 + (\sigma_H)^2\right\}}.$$

5. Results



Spatial profile of the induced electric field at different times (τ) in the QGP created in head-on collisions (Upper panel), and peripheral collisions (bottom panel).

6. Summary and conclusion

- We employed the kinetic theory-based RTA approach to calculate thermoelectric coefficients and induced field. For numerical estimation, we used a quasiparticle model that reproduces the lattice QCD EoS of QGP. To calculate the induced electric field, we use Gubser hydrodynamics
- For the first time, we estimated the induced electric field in QGP solely using the thermoelectric effect
- The maximum electric field produced in head-on and peripheral collisions is *$\sim 0.7\ m_\pi^2$ and $1.0\ m_\pi^2$*, respectively

7. References

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