Coherent emission from QED cascades in pulsar polar caps

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Introduction

Pulsar magnetospheres are thought to be filled with electron-positron plasma generated in pair cascades [1, 2]. The driving mechanism of these cascades is the emission of gamma-ray photons and their conversion into pairs via Quantum Electrodynamics (QED) processes. In this work, we present 2D particle-in-cell simulations of pair cascades in pulsar polar caps with realistic magnetic field geometry that include the relevant QED processes from first principles. Our results show that, due to variation of magnetic field curvature across the polar cap, pair production bursts self-consistently develop an inclination with respect to the local magnetic field that favors the generation of coherent electromagnetic modes with properties consistent with pulsar radio emission. We show that this emission is peaked along the magnetic axis and close to the polar cap edge and may thus offer an explanation for the core and conal components of pulsar radio emission.

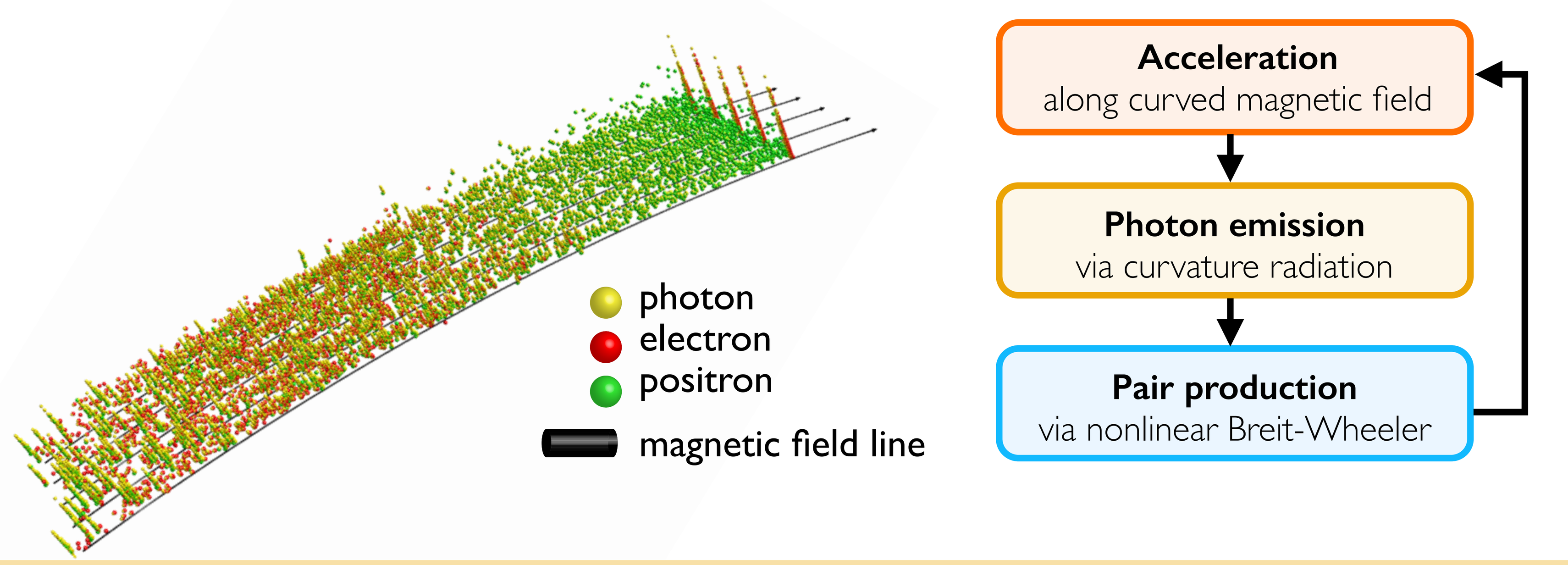

Figure 1: Illustration of a pair cascade in the ultra-intense, curved magnetic field lines of a pulsar polar cap; electrons and positrons emit photons which decay into new pairs in a loop.

Methods

We present particle-in-cell (PIC) simulations of pulsar polar cap discharges. PIC models the plasma as a collection of particles that self-consistently interact with their collective electromagnetic fields through a grid. Our simulations are performed with OSIRIS [3], a fully relativistic, massively-parallel PIC code that includes the relevant QED processes from first principles: in each time step, we evaluate the probability of each particle to produce secondary particles; new simulation particles are created/deleted as needed.

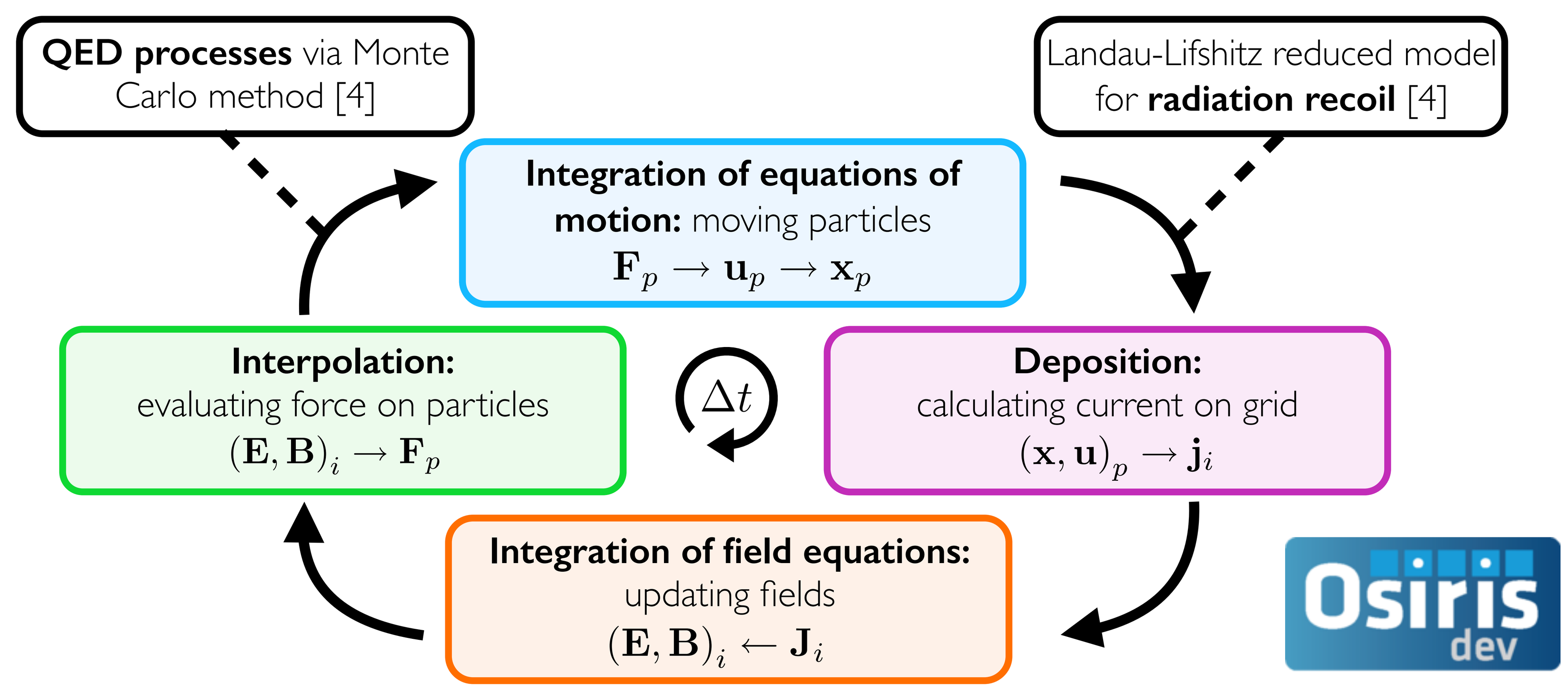

Figure 2: Schematic representation of the particle-in-cell (PIC) simulation loop, including the QED processes relevant in pulsar polar caps.

Results

Our simulations are performed in 2D cylindrical geometry. The simulation domain spans a volume above the surface of the pulsar of $L_R \times L_z = 1.5 \times 2.5\ R_0^2$, where R_0 is the polar cap radius. The domain is discretized with $N_R \times N_z = 6000 \times 10000$ cells, and the simulation time step is $\Delta t c/R_0 = 10^{-4}$. An external dipolar field permeates the simulated volume. Plasma is injected from the lower z boundary. This boundary is a rotating conductor and mimics the NS surface. The last open field line is a perfect conductor.

The main results can be summarized as follows:

- A vacuum gap opens periodically close to the NS surface and QED cascades generate a pair plasma that screens the gap electric field; when the cascade stops, the plasma advects into the magnetosphere
- The pair production bursts do not develop uniformly across the polar cap: (Fig. 3 a-c) pair production is suppressed on the magnetic axis (null magnetic field curvature) and on the polar cap edge (gap electric field drops) — this leads to a direct imprint of the QED processes on the profile of emitted radiation
- Inductive plasma waves [5] generated in the inclined pair production bursts couple (Fig. 3 d) to an electromagnetic mode (O-mode) [6] (Fig. 3 f-g)
- The emitted waves have a frequency comparable to the plasma frequency and have a superluminal phase velocity, resembling radio emission
- Waves are predominantly emitted along $+z/+r$ in a double-peaked structure (Fig. 3 h); however, a fraction of the emitted power is carried by waves that are continuously reflected on the polar cap edge, leading to a drifting component

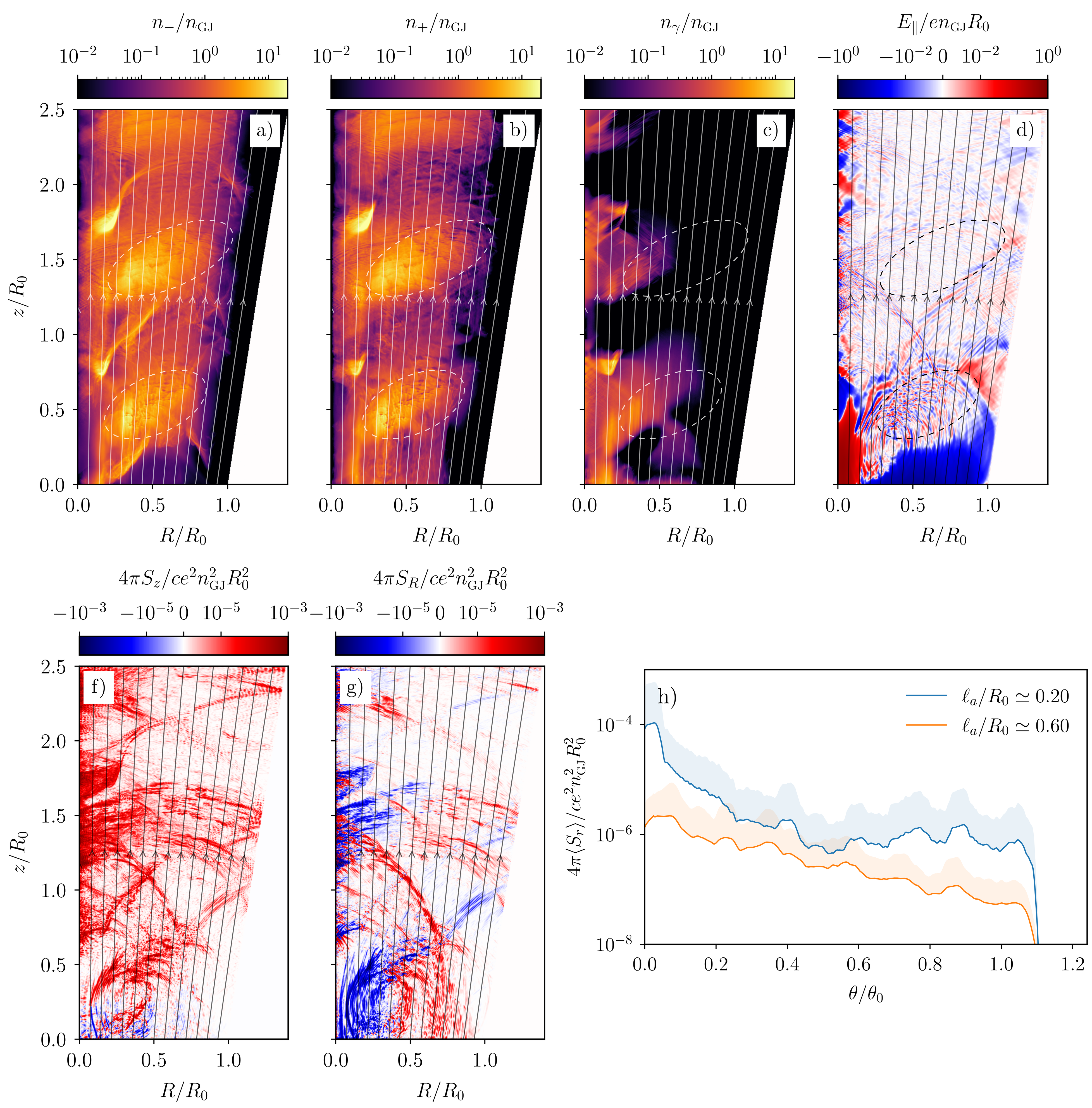

Figure 3: Electron/positron/photon densities (a-c, respectively), electric field component parallel to the background magnetic field (d) and Poynting vector components (f-g) at time $tc/R_0 = 5.4$, where two pair production bursts are visible (see dashed outlines). Magnetic field lines are shown in solid lines. All quantities use normalizations derived from $n_{GJ} = \Omega B/2\pi ce$. Emitted intensity profiles obtained for simulations with pair production bursts with different aspect ratios ℓ_a/R_0.

Conclusions

First *ab initio* simulations of pair cascades in pulsar polar caps

- Vacuum gap is bursty, with plasma blobs periodically launched into the magnetosphere
- Nonuniform pair production bursts generate inductive plasma waves that propagate in all directions
- Conversion to electromagnetic mode with double-peaked intensity profile
- New short time-scale ($\sim 1\ \mu s$) drifting component
- Emitted radiation properties are direct imprints of the QED and plasma kinetic processes

References

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