Upper Field-strength Limit of Fast Radio Bursts

Yu Zhang and Hui-Chun Wu

Institute for Fusion Theory and Simulation and Department of Physics, Zhejiang University, Hangzhou 310027, People’s Republic of China; huichunwu@zju.edu.cn

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Abstract

Fast radio bursts (FRBs) are cosmological radio transients with an unclear generation mechanism. Known characteristics such as their luminosity, duration, spectrum, and repetition rate, etc., suggest that FRBs are powerful coherent radio signals at GHz frequencies, but the status of FRBs near the source remains unknown. As an extreme astronomical event, FRBs should be accompanied by energy-comparable or even more powerful X/γ-ray counterparts. Here, particle-in-cell simulations of ultrastrong GHz radio pulse interaction with GeV photons show that at \( \geq 3 \times 10^{12} \text{ V cm}^{-1} \) field strengths, quantum cascade can generate dense pair plasmas, which greatly dampen the radio pulse. Thus, in the presence of GeV photons in the source region, GHz radio pulses stronger than \( 3 \times 10^{12} \text{ V cm}^{-1} \) cannot escape. This result indicates an upper field-strength limit of FRBs at the source.

Unified Astronomy Thesaurus concepts: Radio transient sources (2008); Radio bursts (1339); Plasma astrophysics (1261)

1. Introduction

Since first discovered in 2007 (Lorimer et al. 2007), fast radio bursts (FRBs) have been recognized as real astronomical events and have gained much research interest (Katz 2018; Platts et al. 2019; Zhang 2020). Although event reports and theoretical models of FRBs have exploded over the past decade, the origin of FRBs remains unclear. Due to large dispersion measures with hundreds or even thousands of cm\(^{-3}\) pc, these radio transients have cosmological origins (Xu & Han 2015) that have been confirmed by several events with located host galaxies (Thornton et al. 2013; Petroff et al. 2016). Therefore, FRBs can serve as novel probes for interstellar and intergalactic matters (Prochaska et al. 2019; Macquart et al. 2020).

Assuming an isotropic emission, the luminosity of FRBs ranges from \( 10^{38} \) to \( 10^{43} \text{ erg s}^{-1} \) (Thornton et al. 2013; Zhang 2018), many orders of magnitude more powerful than radio pulsars. Meanwhile, the ultrahigh brightness temperature \( \sim 10^{15} \text{K} \) (Katz 2018; Zhang 2020) indicates that FRB radiations must be coherent. The millisecond duration implies that the source is limited to hundreds of kilometers in size, which points to compact objects in the universe, such as white dwarfs, neutron stars, or black holes. The observed FRB 200428 (Bochenek et al. 2020; CHIME/FRB 2020; Lin et al. 2020) in the Milky Way associated with a hard X-ray burst from magnetar SGR 1935+2154, suggests magnetars can generate FRBs.

Many models of FRBs (Katz 2018; Platts et al. 2019; Zhang 2020) have been proposed. Possible FRB sources are located in or outside of the magnetospheres of neutron stars. In the magnetosphere, the radiation mechanisms include plasma maser emissions from relativistic plasmas or plasma instabilities (Lyubarsky 2020), and curvature radiation of charged bunches (Katz 2014; Kumar et al. 2017; Lu & Kumar 2018; Yang et al. 2020). Outside of the magnetosphere, relativistic shocks driven by outflows from neutron stars may also induce FRBs (Lyubarsky 2014; Waxman 2017; Metzger et al. 2019; Beloborodov 2020). Although the emission region of the FRBs in neutron stars is still being debated, most theoretical models show that FRBs are accompanied by energy-comparable or even more powerful counterparts in X- and γ-ray bands of keV to TeV (Chen et al. 2020). The observed X-rays from FRB 200428 are four orders of magnitude more energetic than the radio emission.

FRBs have been detected in the range of 0.3–8 GHz (Zhang 2020), with a bandwidth of hundreds of MHz limited by the detection band of radio telescopes. The coherent GHz radiation implies an emitter in the submeter scale. In the immediate vicinity of the emitters, FRBs correspond to an extremely strong microwave. Research on this extreme microwave is rare (Wu 2016). In this paper we simulate the interaction between ultrastrong GHz radio waves and GeV gamma photons. It is found that at a field strength of \( 3 \times 10^{12} \text{ V cm}^{-1} \), dense pair plasmas are produced by quantum cascades that significantly dampen the radio pulses. This process should occur in the FRB emission region and constrains the radiation intensity near the emitters.

2. Interaction of Strong Radio Wave and High-energy Particles

2.1. Estimation of the FRB Field Strength Near the Source

The FRB energy can be expressed as \( W = d\Omega R^2 cT\varepsilon_0 E^2 \), where \( d\Omega \) is the solid angle of the FRB emission cone, \( E \) is the field amplitude at a distance \( R \) from the source, \( T \approx 1 \text{ ms} \) is the duration, \( c \) is the light speed, and \( \varepsilon_0 \) is the vacuum permittivity. For isotropic emission (\( d\Omega = 4\pi \)), the energy range is estimated to be \( W_i = 10^{38}–10^{42} \text{ erg} \), so that the field strength \( E \) can be obtained from

\[
W_i = 4\pi R^2 cT\varepsilon_0 E^2. \tag{1}
\]

It is stressed that here \( R \) only refers to a distance from the FRB emitters, which may be located in the inner or outer magnetospheres of neutron stars.

The blue region in Figure 1 shows the possible \( E \) range of FRBs as a function of \( R \). The field strength range is
\[
1.7 \times 10^9 - 5.4 \times 10^{12} \text{ V cm}^{-1} \text{ for } R = 100 \text{ km}. \text{ The solid line marks the Schwinge field } E_s = 1.32 \times 10^{16} \text{ V cm}^{-1}. \text{ The dashed line is the critical field strength } 3 \times 10^{12} \text{ V cm}^{-1} \text{ predicted by our simulations, where high-energy photons can trigger strong quantum cascades and radiation damping. For a point source, } E \text{ in Equation (1)} \text{ will diverge when } R \rightarrow 0. \text{ The actual emission zone should consist of many emitters and have a total emission surface of area } S. \text{ The emission energy has } W = S \epsilon E_s^2, \text{ similar to Equation (1). For } S = 10^6 \text{ km}^2, \ E = 1.95 \times 10^9 - 6.14 \times 10^{12} \text{ V cm}^{-1}. \]

### 2.2. One-dimensional PIC-QED Code

To investigate the interaction between ultrastrong FRBs and gamma photons, we use the one-dimensional particle-in-cell (PIC) simulation code JPIC1d-QED, where avalanche quantum-electromagnetic (QED) production of positron-electron pairs through the Breit–Wheeler process and nonlinear inverse Compton scattering (Erber 1966; Kirk et al. 2009; Elkina et al. 2011) are included in the existing code JPIC1d (Wu 2011). Production of positron-electron pairs and photons are determined by a Monte Carlo algorithm with quantum generation rates (Elkina et al. 2011; Nerush et al. 2011; Wang et al. 2017). A particle-merging scheme is used to deal with the rapidly increased particles in the avalanche. To suppress numerical noises typically encountered in PIC-QED simulations, we adopt a five-point particle interpolation for the positrons/electrons. The code has been benchmarked for single-electron quantum cascades in a static magnetic field (Anguelov & Vankov 1999; Elkina et al. 2011) and has reproduced the results of ultraintense laser QED breakdowns triggered by a single electron (Nerush et al. 2011).

The Breit–Wheeler process generates electron–positron pairs by annihilation of gamma photons in intense electromagnetic fields. Inverse Compton scattering in turn generates gamma photons through the FRB-field-accelerated-relativistic electrons and positrons. Both these effects are measured by (SI units)

\[
\chi \simeq \frac{\gamma}{E_s} \sqrt{(E + v \times B)^2 - (v \cdot E)^2} / c^2,
\]

where \( \gamma \) is the Lorentz factor of electrons/positrons and photons, \( v \) is the particle speed, and \( E \) and \( B \) are the electric and magnetic fields, respectively. For photons, \( \gamma = \epsilon / mc^2 \) and \( |\epsilon| = c, \epsilon \) is the photon energy, and \( m \) is the electron rest mass. Obvious QED cascades can occur for \( \gamma \approx 0.1 \), and massive production of pairs and photons occurs when \( \gamma \rightarrow 1 \).

### 2.3. Nanosecond-duration Radio Pulse and GeV Gamma Photon

A hundreds-of-MHz bandwidth implies a coherent time of a few nanoseconds; thus, the millisecond FRBs are expected to contain many coherent nanosecond subpulses. We now consider the interaction between such nanosecond subpulses and gamma photons and attempt to find the critical field strength for substantial quantum cascades within the subcycle of radio waves. Dense pair plasmas generated in the subcycle can dampen a great portion of the entire multiple-cycle pulse (Nerush et al. 2011). Since FRBs are highly polarized, we assume the bipolar waveform \( E_s = E_0 \exp(-t^2/\tau^2) \sin(\omega_0 t) \) in our simulations, where \( \omega_0/2\pi = 1 \) GHz is the central frequency, and \( \tau = 0.3 \lambda/c \) for wavelength \( \lambda \approx 30 \) cm. The radio pulse propagates along the \( x \)-axis and the peak field strength is \( E_p = 0.636E_0 \) due to the carrier-envelope phase effect.

Although TeV radiations are also predicted to associate with FRB events, here we focus on the GeV-level triggering particles, which are not a rigorous requirement for extreme environments in neutron stars (Becker 2009). Quantum cascade is sensitive to the interaction angle between fields and particles. From Equation (2), one obtains

\[
\chi \approx \frac{\gamma}{E_s} (E_s - v_s B_\parallel) = \frac{2E_s}{E_s} \left( 1 - \frac{v}{c} \cos \theta \right),
\]

where \( \theta \) is the angle between the particle velocity \( v \) and the \( x \)-axis. The QED effects are negligible for \( \theta = 0 \) and most pronounced for head-on collision with \( \theta = 180^\circ \). For \( \gamma = 2000 \) and \( \theta = 180^\circ \), the field strength for quantum cascades at \( \chi = 1 \) is \( E = 3.3 \times 10^{11} \) V cm\(^{-1}\).

It is difficult for the GeV-charged particles to trigger quantum cascade in the FRB fields, since the electrons and positrons will be decelerated in the longitudinal direction by the ultrastrong ponderomotive force of FRB fields, then will get reflected and copropagate (at \( \theta \approx 0 \)) with the radio waves. Such reflection occurs for the incident particle with energy less than \( \gamma r_{\parallel} \approx a_0/4 \) (Wu et al. 2011), where \( a_0 = E/mc_0 \). For 1 GHz radio waves with \( E = 3.3 \times 10^{11} \) V cm\(^{-1}\), one has \( a_0 = 3.1 \times 10^6 \) and \( \gamma r_{\parallel} \approx 7.8 \times 10^5 \), i.e., 0.4 TeV. However, as to be shown below, if the pair particles can emit energetic gamma photons, quantum cascade will be possible since the gamma photons can freely penetrate into the strong FRB fields and annihilate into electron–positron pairs.

### 3. Results

The first simulation is conducted for \( E_p = 2.68 \times 10^{12} \) V cm\(^{-1}\), which corresponds to \( a_0 = E_p/mc_0 \approx 2.5 \times 10^7 \) and magnetic field of \( E_p/c \approx 0.89 \times 10^{10} \) Gauss. The simulation box is 2\( \lambda \) in length with a spatiotemporal resolution of 10,000 grids per wavelength/cycle. Ten 1 GeV photons are simultaneously incident to the FRB pulse with \( \theta = 120^\circ \).

Figure 2 shows photon-triggered pair plasma sparks in the comoving frame of the radio pulse. Obvious QED cascades occur at \( E_s \approx 0.7E_{\parallel} \), where annihilation of incident photons generates hundreds of \( \chi \approx 0.1 \) pair particles, which are in turn violently accelerated by the intense FRB fields to...
ultrarelativistic energies and emit high-energy photons. The latter are further annihilated into electron–positron pairs by the FRB fields. As shown in Figure 2, three distinct plasma clumps appear, they grow and finally merge into a plasma sheet within \( \sim 1 \) ns. The plasma density increases exponentially before the clump merges and saturates at \( t = 1.6 \lambda / c \) with the peak density of \( 7.2 \times 10^6 n_c \). Here, \( n_c \approx 1 \times 10^{13} (\text{cm}/\lambda)^2 \text{cm}^{-3} = 1.11 \times 10^{10} \text{cm}^{-3} \) is the critical density for 1 GHz waves. After \( t = 1.6 \lambda / c \), the pair plasma sheet comoves with the field, and hence quantum cascades cease. For an ultrarelativistic field, the plasma density for screening the field is \( \sim a_0 n_c \). The plasma sheet has a density lower than \( a_0 n_c = 2.5 \times 10^7 n_c \) and its thickness is 0.01 \( \lambda \). Thus, it causes only a small distortion on the FRB field.

Figure 3 shows the electron and photon energy spectra. During the active cascades at \( t \sim 1.3 \lambda / c \), the particles and photons are synergetic with each other and have almost the same maximum energy. However, due to the wave-field acceleration, the charged particle energy is always more concentrated than the photon energy. After the saturation at \( t \sim 1.5 \lambda / c \), the charged particles are free from radiation damping, and their energy quickly overtakes that of the photons. They are more monoenergetic than before, and have an average energy \( \sim 0.2 \) TeV at \( t = 1.8 \lambda / c \).

We increase the peak wave field to \( E_p = 3 \times 10^{12} \) V cm\(^{-1} \) with \( a_0 = 2.8 \times 10^3 \). Figure 4 shows the electric field \( E_x \) and pair plasma density \( n_e \). Due to the generated pair plasmas, partial field screening starts at \( t \sim 1 \lambda / c \). Then the plasma density dramatically increases and exceeds the relativistic critical density \( a_0 n_c \sim 2.8 \times 10^7 n_c \). The field screening then becomes complete in the plasma with \( n_e > a_0 n_c \), and the pair plasma expands toward the front side and further grows to the back side. Figure 5 shows the electron energies distribution. At the front of the plasma, electrons/positrons are further accelerated along the \( x \)-axis to higher energies. According to Equation (3) the QED effects become weak and pairs are no longer produced. On the back side, the oscillating charged particles on the vacuum-plasma boundary continue to collide...
with the right-going field and produce new pairs. However, Figures 5(b) and (c) show that due to the continuous radiation damping, the energy of these particles is suppressed, as compared with that of the accelerated particles on the right front. In Figure 5(c), one can see that a plasma spark appears downstream in the second half-cycle. It is triggered by the emitted photons from the QED-active back side of the pair plasma region. Such sparks could dampen the FRB emitted photons from the QED-active back side of the pair plasma region. Such sparks could dampen the FRB field in the more extended space.

Energy spectra of electrons and photons are given in Figure 6. During the active quantum cascades at $t = 1 \lambda/c$, charged particles and photons have similar spectra as that in Figure 3. After the complete field screening, the high-energy part of the spectra at $t = 1.4 \lambda/c$ and $1.8 \lambda/c$ in Figure 6(a) comes from the field-accelerated particles at the plasma front. Depletion of GeV photons at $1 \lambda/c < t < 1.4 \lambda/c$ can be attributed to photon annihilation and production of pair plasmas.

Gamma photons above 1 GeV are observed to more easily cause the field depletion. We also carried out the simulations for charged particles in the GeV–TeV range and found that tens of GeV are required to trigger significant radiation damping. In 3D space, pair plasmas will fill the main radio-field volume, as demonstrated in the multidimensional PIC simulation of ultraintense laser breakdown triggered by a single electron in a vacuum (Nerush et al. 2011). On the other hand, here we have only tens of photons interacting with the FRB. Existing models invoke photons with comparable high energy (GeV–TeV) coexisting with the FRBs. The results here indicate that such high-energy photons will fully deplete the FRB.

For FRBs propagating across the neutron star magnetic field $B_{\text{NS}}$, incoherent scattering by magnetospheric plasmas could be significant and gamma rays produced in this process could trigger severe cascades in the FRB (Beloborodov 2021). When radio waves propagate along the background magnetic field $B_{\text{NS}}$, gamma-photon annihilation due to $B_{\text{NS}}$ is negligible due to the vanishing term $v \times B_{\text{NS}} = 0$ in Equation (2). Therefore, our results are more applicable for FRBs escaping from the polar regions of neutron stars.

As an extremely efficient radio burst, the plasma/beam emitter must be able to coexist with its self-field and radiation field, and will not induce severe field breakdown within both emitter and FRB bodies. According to our results, this requires that the plasma density in or nearby the emitter should be lower than the level of $\rho_{\text{crit}}$ for less field screening, and the plasma/beam driver could mainly propagate along the radiation direction for negligible pair cascades. The driver can produce high-energy gamma rays along its momentum direction. By Compton backscattering from background plasmas, these gamma rays could turn back to scatter the FRB field as studied here.

4. Conclusion

We have investigated radiation dampings of FRBs triggered by high-energy photons in GeV. At the field amplitude of $3.0 \times 10^{12}$ V cm$^{-1}$, dense pair plasmas are generated within a subcycle of these radio transients. The plasma generation and radiation absorption lead to the breakdown of FRB fields. This energy depletion can critically limit the field strength of FRBs around their emitters. Similar QED effects can also be expected during other stages of FRB propagation. Our work also implies that QED effects (Katz 2017; Philippov et al. 2020) could be indispensable near the FRB emitter.

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ORCID iDs

Yu Zhang @ https://orcid.org/0000-0001-5981-8817
Hui-Chun Wu @ https://orcid.org/0000-0001-5389-8115