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Abstract. LOPES is set up at the location of the KASCADE-Grande extensive air shower experiment in Karlsruhe, Germany and aims to measure and investigate radio pulses from Extensive Air Showers. Data taken during half a year of operation of 10 LOPES antennas (LOPES-10), triggered by showers observed with KASCADE-Grande have been analyzed. We report about results of correlations found of the measured radio signals by LOPES-10 with shower parameters.

1. Introduction

The traditional method to study extensive air showers (EAS) is to measure the secondary particles with sufficiently large particle detector arrays. In general these measurements provide only immediate information on the status of the air shower cascade on the particular observation level. This hampers the determination of the properties of the EAS inducing primary as compared to methods like the observation of Cherenkov and fluorescence light, which provide also some information on the longitudinal EAS development, thus enabling a more reliable access to the intended information (Haungs, Rebel & Roth, 2003).

In order to reduce the statistical and systematic uncertainties of the detection and the reconstruction of EAS, especially with respect to the detection of cosmic particles of highest energies, there is a current methodical discussion about new detection techniques. In this sense the radio emission accompanying cosmic ray air showers, though first observed in 1964 by Jelley et al. (1965) at a frequency of 44 MHz, is a somehow ignored EAS feature. This fact is due to the former difficulties with interferences of radio emission from other sources in the environment and of the interpretation of the observed signals. However, the studies of this EAS component have experienced a revival by recent activities.

Recent theoretical studies by Falcke & Gorham (2003) and Huege & Falcke (2003,2005) of the radio emission in the atmosphere are embedded in the scheme of coherent geosynchrotron radiation. Here, electron-positron pairs generated in the shower development gyrate in the Earth's magnetic field and emit radio pulses by synchrotron emission. During the shower development the electrons are concentrated in a thin shower disk ($< 2\,\mathrm{m}$), which is smaller than one wavelength (at $100\,\mathrm{MHz}$) of the emitted radio wave. This situation provides the coherent emission of the radio signal. Detailed Monte-Carlo simulations (Huege et al., 2006) lead to valuable expectations of the radio emission at frequencies of $10\,\mathrm{MHz}$ to $500\,\mathrm{MHz}$ with a coherent emission at low frequencies up to $100\,\mathrm{MHz}$. Such expectations will be compared to the recent experimental results, in particular provided by LOPES.

The present contribution sketches briefly recent results of the LOPES project (Falcke et al., 2005) obtained by analyzing the correlations of radio data taken with the first 10 LOPES antennas with shower parameters reconstructed by KASCADE-Grande. KASCADE-Grande (Navarra et al., 2004) is an extension of the multi-detector setup KASCADE (KArlsruhe Shower Core and Array DEtector) built in Germany (Antoni et al., 2003), measuring air showers in the primary energy range of $100\,\mathrm{TeV}$ to $1\,\mathrm{EeV}$ with high precision due to the detection of all charged particle types at sea-level, i.e. the electromagnetic, the muonic, and the hadronic shower components. Hence, LOPES, which is designed as digital radio interferometer using large bandwidths and fast data processing, profits from the reconstructed air shower observables of KASCADE-Grande.

2. LOPES-10: Layout and data processing

The basic idea of the LOPES project was to build an array of relatively simple, quasi-omnidirectional dipole antennas, where the waves received are digitized and sent to a central computer. This combines the advantages of low-gain antennas, such as their large field of view, with those of high-gain antennas, like the high sensitivity and good background suppression. With LOPES it is possible to store the received data stream for a certain period of time, i.e. at a detection of a transient phenomenom like an air shower retrospectively, a beam in the desired direction can be formed. To demonstrate the capability to measure air showers with these antennas, LOPES is built-up at the air shower experiment KASCADE-Grande. The air shower experiment provides a trigger of high-energy events and, additionally, with its direction reconstruction a starting point for the radio data analyses, in particular for the so called beam forming.

In the current status LOPES operates 30 short dipole radio antennas (LOPES-30, see Isar
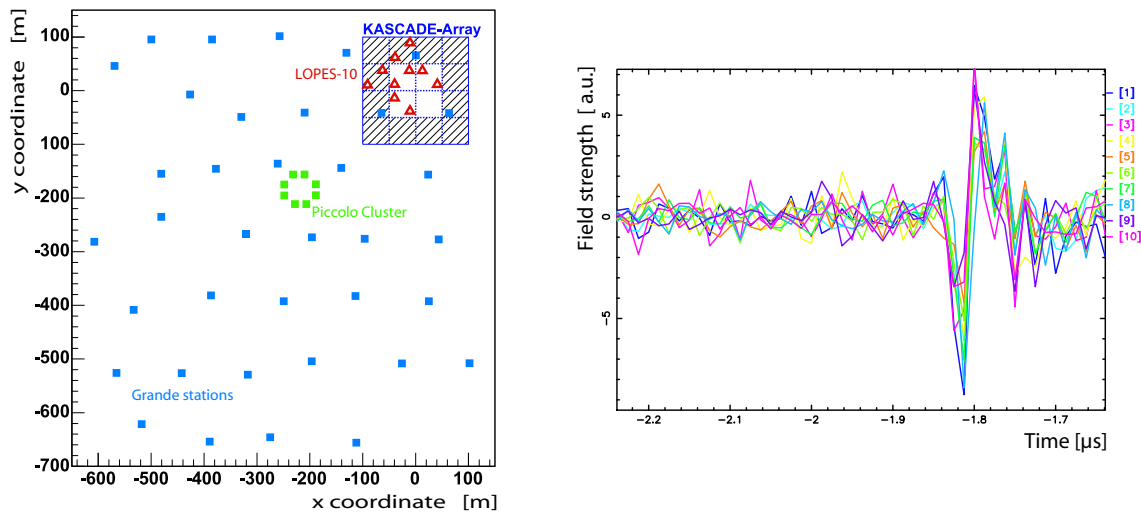
Figure 1. Left: Sketch of the KASCADE-Grande – LOPES-10 experiment: The 16 clusters (12 with muon counters) of the KASCADE field array, the distribution of the 37 stations of the Grande array, and the small Piccolo cluster for fast trigger purposes are shown. The location of the 10 LOPES radio antennas is also displayed. Right: Raw signals of the individual antennas for one event example. The signals at this stage are prepared for the beam-forming based on shower observables reconstructed by KASCADE-Grande.

et al., 2006), data of the first 10 antennas forming LOPES-10 are presently analyzed and first results will be discussed in the following.

The ten antennas, positioned within the original KASCADE array (Fig. 1, left panel), operate in the frequency range of $40-80$ MHz and are aligned in east-west direction, i.e. they are sensitive to the linear east-west polarized component of the radiation, but can be easily changed into the perpendicular polarization by turning the antennas. The read out window for each antenna is 0.8 ms wide, centered around the trigger received from the KASCADE array. The sampling rate is 80 MHz. The geometry of the antenna and the aluminum ground screen give the highest sensitivity to the zenith and half sensitivity to zenith angles of $43° - 65°$, dependent on the azimuth angle. LOPES data are read out if KASCADE triggers by a high multiplicity of fired stations, corresponding to primary energies above $\approx 10^{16}$ eV. Such showers are detected at a rate of ≈ 2 per minute.

The LOPES data processing includes several steps (Horneffer, 2005). First, the relative instrumental delays are corrected using a known TV transmitter visible in the data. Next, the digital filtering, gain corrections and corrections of the trigger delays based on the known shower direction (from KASCADE) are applied and noisy antennas are flagged. Then a time shift of the data is done and the combination of the data is performed calculating the resulting beam from all antennas. This geometrical time shift (in addition to the instrumental delay corrections) of the data, is the time difference of the pulse coming from the given direction to reach the position of the corresponding antenna compared to the reference position. This shift is done by multiplying a phase gradient in the frequency domain before transforming the data back to the time domain. The data is also corrected for the azimuth and zenith dependence of the antenna gain. Figure 1, right panel, shows a particularly bright event as an example. A crucial element of the detection method is the digital beam forming which allows to place a narrow antenna beam in the direction of the cosmic ray event. To form the beam from the time shifted data, the data from each pair of antennas is multiplied time-bin by time-bin, the

resulting values are averaged, and then the square root is taken while preserving the sign. We call this the cross-correlation beam or CC-beam. Finally, there is a quantification of the radio shower parameters: Although the shape of the resulting pulse (CC-beam) is not really Gaussian, fitting a Gaussian to the smoothed data (by block averaging over 3 samples) gives a robust value for the peak strength, which is defined as the height of this Gaussian. The error of the fit results gives also a first estimate of the uncertainty of this parameter. The finally obtained value ϵ_ν, which is the measured amplitude divided by the effective bandwidth, is compared with further shower observables from KASCADE-Grande, e.g. the angle of the shower axis with respect to the geomagnetic field, the electron or muon content of the shower, the estimated primary energy, etc.

3. Results of LOPES 10

The LOPES-10 data set corresponds to a measuring period of seven months and is subject of various analyses addressing different scientific aspects. With a sample asking for high quality events the proof of principle for detection of air showers in the radio frequency range has been achieved (Falcke et al., 2005).

From the triggered events falling inside the area of the original $200 \times 200\,\mathrm{m}^2$ large KASCADE array more than 220 events with a clear radio signal could be detected. The analysis of these events concentrates on the correlations of the radio signal with all shower parameters, in particular with the arrival direction and with the shower size, i.e. the primary energy of the shower.

Further interesting features are currently being investigated with a sample of very inclined showers (Petrovic et al., 2006) and with a sample of events measured during thunderstorms (Buitink et al., 2006). The former sample is of special interest for a large scale application of this detection technique, as due to the low attenuation in the atmosphere also very inclined showers should be detectable with high efficiency. With LOPES one could show that events above $70°$ zenith angle still emit a detectable radio signal. The measurements during thunderstorms are of interest to investigate the role of the atmospheric electric field in the emission process.

Besides the analyses of events with the core inside the antenna setup, KASCADE-Grande gives the possibility to search for distant events. For each (large) shower triggering KASCADE, the information from the extension of KASCADE, i.e. from the Grande array, is available. From that information the shower can be reconstructed even if the core is outside the original KASCADE area, and a radio signal can be searched for events which have distances up to $800\,\mathrm{m}$ from the center of the antenna setup.

The time shift procedures described above are relatively safe when the shower parameters for core and axis are reconstructed with high accuracy, i.e. provided by the reconstruction of data taken with the original KASCADE field array. Due to the high sampling area the accuracy of the core position and direction is good enough to obtain satisfying coherence of the radio signals. But a shower reconstruction using data from the Grande array is required for shower cores outside KASCADE. The Grande stations cannot assure an accuracy comparable with the original KASCADE array. This leads to events whose reconstructed radio signals do not fulfill the requirements to qualify as detected in the radio channel. Therefore, a so-called optimized beam-forming is performed (Apel et al., 2006) which searches for maximum coherence by varying the core and the direction around the values provided by the Grande reconstruction ($\sigma_{xy} \approx 10\,\mathrm{m}$, $\sigma_{dir} \approx 0.5°$ for $E_0 > 50\,\mathrm{PeV}$).

Figure 2 shows as an example the result of such an optimized beam-forming for an event with a mean distance between shower axis and radio antennas of $150\,\mathrm{m}$ and a primary energy of $\approx 4 \cdot 10^{17}\,\mathrm{eV}$. In the upper part of the figure the raw time-series of the 10 antennas and the corresponding CC-beam including the fit are shown, obtained by using the Grande reconstructed parameter set, which is $289.5°$ in azimuth and $41.1°$ in zenith. The lower part shows the same
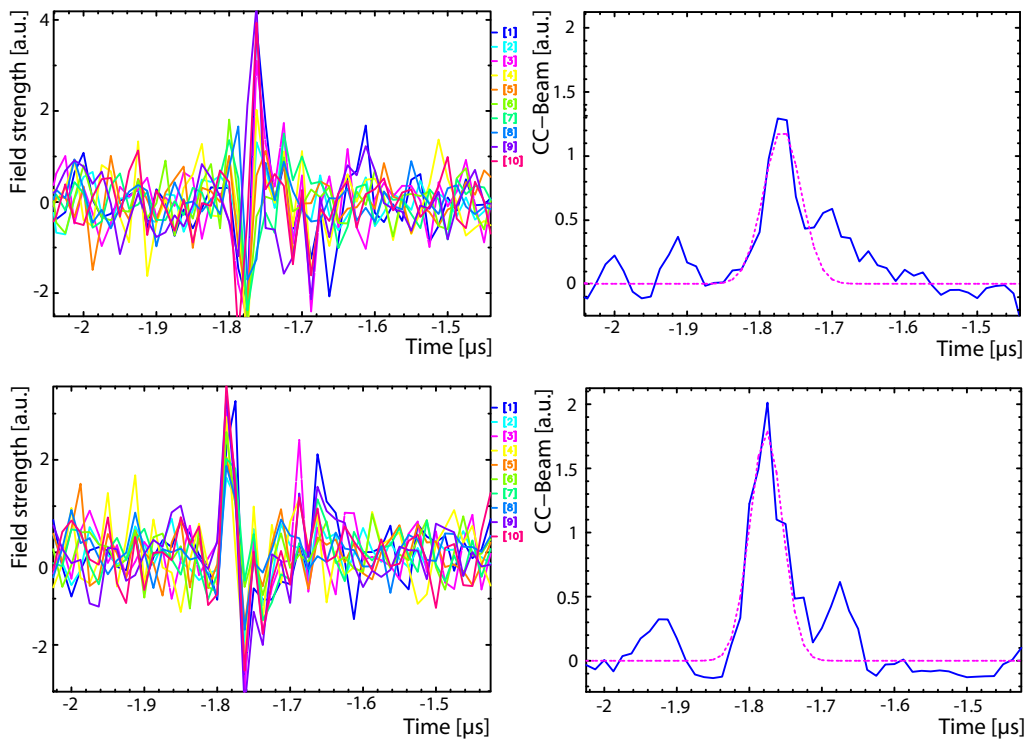
Figure 2. Event example: Upper panels: Signals of the individual antennas and result of the beam-forming (full line: CC-beam; dotted line: Gaussian fit) based on shower observables reconstructed by Grande; Lower panels: Signals of the individual antennas and result of the optimized beam-forming in order to maximize the radio coherence.

event by choosing those starting parameters for the beam-forming which led to the maximum coherence, i.e. the highest radio pulse. A shift of approximately two degree in the direction and $\approx 3\,\mathrm{m}$ in the core was necessary to find this maximum coherence. An increase of 50% is seen in the CC-beam estimator after the optimized beam-forming.

For the sample of Grande reconstructed showers also several hundred events (372 in 6 months data taking) could be detected, where in particular, due to the larger distances of the antennas to the shower core, the lateral behavior of the radio emission can be investigated (Apel et al., 2006).

3.1. Correlation of the radio signal with primary particle energy

One of the most important questions to be answered is the dependence of the emitted and measurable electric field strength with the primary energy of the incidental cosmic ray. Both samples, the central and the distant events were used to investigate this. As example, figure 3 (left panel) depicts the dependence of the reconstructed averaged radio pulse height with the primary energy of the cosmic particles. The shown correlation supports the expectation that the field strength increases by a power-law with an index close to one with the primary energy, i.e. that the received power of the radio signal increases quadratically with the primary energy of the cosmic rays. This behavior is confirmed by analyzing the distant events sample. Simulations show a similar dependence, but in addition a weak dependence of the index of the power-law on the distance to the shower center (Huege & Falcke, 2005), which still has to be proven using higher statistical accuracy in the measurements.
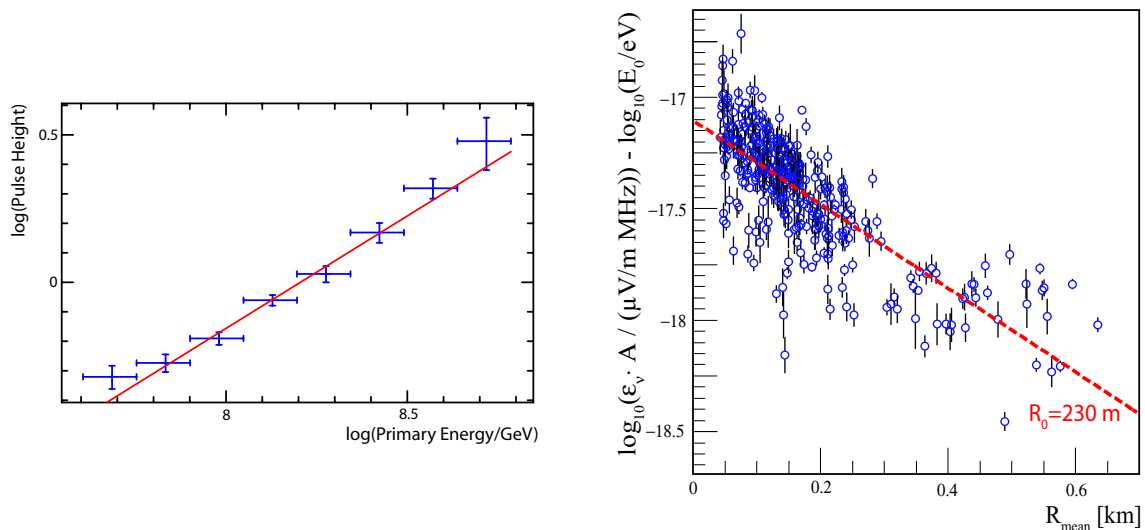
Figure 3. Left: Radio pulse height of the detected events (with shower core inside the KASCADE array and corrected for the geomagnetic angle) plotted versus the primary particle energy as reconstructed by KASCADE (Horneffer, 2006). Right: Correlation (sample of distant events) of the pulse height corrected for primary energy with the mean distance of the shower axis to the radio antenna system. The line shows the result of a fit with an exponential function.

3.2. Correlation of the radio signal with distance to the shower core

LOPES-10 detect clear EAS radio events at more than $500\,\mathrm{m}$ distance from the shower axis for primary energies below 10^{18} eV. That itself is an remarkable result, but in addition, an important issue is the functional form of the dependence of the radio field strength with distance to the shower axis. In particular, the lateral scaling parameter is of high interest for the further development of the radio detection technique.

After linear scaling of the pulse amplitude ϵ_ν (corrected value of the CC-beam estimator after optimized beam-forming) with the primary energy estimated by KASCADE-Grande a clear correlation with the mean distance of the shower axis to the antennas is found (Fig. 3, right panel). This correlation can be described by an exponential function with a scaling radius in the order of a few hundred meters. Fitting the present data set by explicitly assuming an exponential function, R_0 results to $230 \pm 51\,\mathrm{m}$. Such an exponential dependence of signal to distance is expected by detailed simulations of the geosynchrotron effect with a scaling radius of ~ 100 to $\sim 800\,\mathrm{m}$, increasing with increasing zenith angle (Huege & Falcke, 2005), and by measurements of CODALEMA (Ardouin et al., 2005). Following the formula by Allan (1971) an exponential behavior with a scaling parameter of $R_0 = 110\,\mathrm{m}$ is expected for vertical showers. One has to note that for the data presented in figure 3 the missing correction to the zenith angle dependence surely distorts the obtained scaling parameter.

3.3. Efficiency of the radio detection

With the distant event sample a first investigation of the detection threshold in terms of primary energy and the efficiency of the detection could be performed. Figure 4 shows the efficiency in the detection and reconstruction of a clear radio signal versus the primary energy of the incoming cosmic rays. The selection is performed by using Grande reconstructed shower parameters, only without any information on the radio signal. Concerning the overall detection threshold an increasing efficiency with increasing primary energy reaching approximately 60% for primary energies above $2 \cdot 10^{17}$ eV is found with LOPES-10. An aggravating circumstance for missing detection even at high energies is the fact that with LOPES-10 only one polarization direction
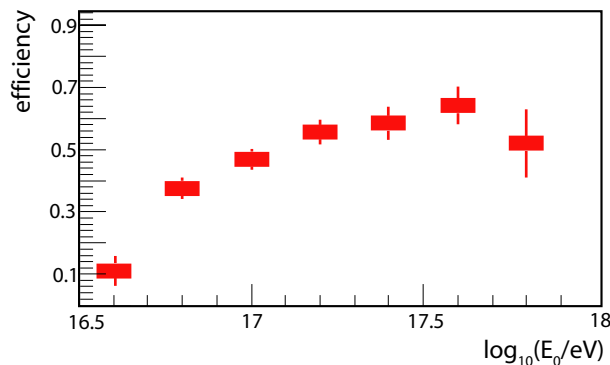
Figure 4. Efficiency for the radio detection (distant event sample) versus primary energy.
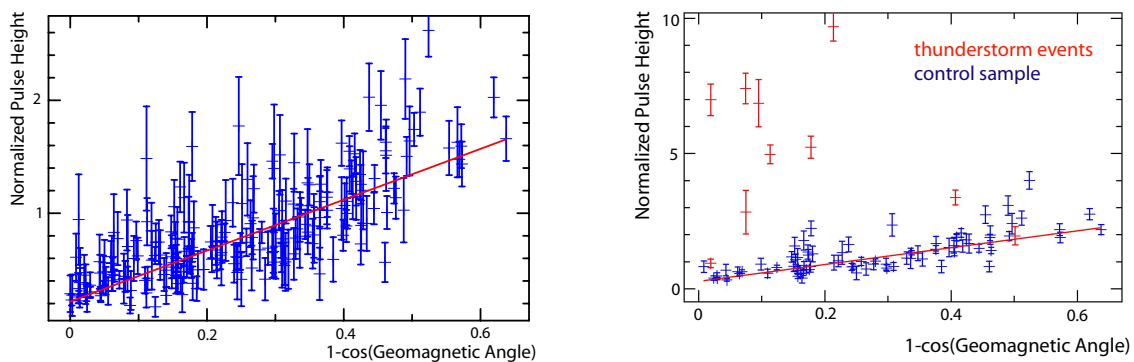

Figure 5. Left: Radio pulse height normalized with the muon number and distance to the shower axis plotted versus the cosine of the angle to the geomagnetic field. The error bars are the statistical errors. The used sample is that with central events. Right: Normalized pulse height of a control sample of detected events and those detected during thunderstorms plotted against the geomagnetic angle. The lines are fits to the data to describe the correlation.

is measured. In addition the direction of the shower axis plays a role: Simulations (Huege & Falcke, 2005) expect that the emission mechanism in the atmosphere and therefore also the radio signal strength depend on the zenith, on the azimuth, and as a consequence on the geomagnetic angle. Indeed, our analyses of the LOPES data have shown that there are preferred directions for enhanced radio signals, or vice versa, there is no radio signal detection for specific shower conditions, especially at the detection threshold.

3.4. Correlation of the radio signal with the geomagnetic angle.
Figure 5, left panel shows the correlation between the normalized reconstructed pulse height of the events with the geomagnetic angle. Normalized here means, that the detected pulse height is corrected for the dependence on the muon number, i.e. to a large extent, the primary energy. The clear correlation found suggests a geomagnetic origin for the emission mechanism. This dependence could be confirmed by analyzing very inclined showers (though with much lower statistics), but with that sample a much larger range of the geomagnetic angle could be considered (Petrovic et al., 2006), and by measurements of both polarization directions.

3.5. The radio signal in measurements during thunderstorms
We examine the contribution of an electric field to the emission mechanism theoretically and experimentally. Two mechanisms of amplification of radio emission are considered: the

acceleration radiation of the shower particles and the radiation from the current that is produced by ionization electrons moving in the electric field. We selected LOPES data recorded during thunderstorms, periods of heavy cloudiness and periods of cloudless weather. We find that during thunderstorms the radio emission can be strongly enhanced (Fig. 5, right panel). No amplified pulses were found during periods of cloudless sky or heavy cloudiness, suggesting that the electric field effect for radio air shower measurements can be safely ignored during non-thunderstorm conditions (Buitink et al., 2006).

4. Summary

LOPES is running and continuously takes data in coincidence with the air shower experiment KASCADE-Grande. The first results are very promising with respect to the proof of detection of radio flashes from cosmic rays.

With LOPES-10 events with primary energies even below 10^{17} eV were detected in the radio domain, which is remarkably low considering the noisy environment at the experimental site and the missing measurements of the second polarization direction.

One of the most interesting results of the LOPES-10 data analysis is the presence of clear EAS radio events at more than 500 m distance from the shower axis for primary energies below 10^{18} eV.

In addition, the clear correlation of the measured radio pulse with the geomagnetic angle suggests a geomagnetic origin for the emission mechanism.

Finally, the found quadratic dependence of the radio power on the primary energy will make radio detection to a cost effective method for measuring air showers of the highest energy cosmic rays and probably also cosmic neutrinos.

With LOPES-30 we will be able to follow the main goal of the LOPES project: The calibration of the radio emission in extensive air showers.

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