Cold Readout Electronics for Liquid Argon TPCs in the DUNE experiment

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Abstract. The liquid Argon TPC (LArTPC) technology is used in DUNE, the Deep Underground Neutrino Experiment, to achieve its goals as the leading-edge international experiment for neutrino science and proton decay studies. The first 10 k-ton DUNE far detector module will employ wired-based anode planes with cold readout electronics (CE) installed inside the cryostat. The CE developed for cryogenic temperatures (77-89K) operation is an optimal solution that achieves excellent noise performance and decouples the electrode and cryostat design from the readout design. This paper reviews the experience of ProtoDUNE single-phase detector located at the CERN Neutrino Platform and provides an overview of the progress of the CE development, including recent results from system integration tests involving the characterization of new versions of the cryogenic ASICs and front-end motherboards mounted on small scale anode planes immersed in cryogenic liquids.

1. Introduction

The Deep Underground Neutrino Experiment (DUNE) is a leading-edge, international experiment for neutrino science and proton decay studies [1]. DUNE will consist of near and far detectors that will take data in the neutrino beam from the Fermilab's Long Baseline Neutrino Facility (LBNF) starting in 2028. The far detector shown in Fig. 1 will be installed about 1.5 km underground at the Sanford Underground Research Laboratory (SURF) in Lead, South Dakota, 1,300 kilometers downstream of the source. The first module of far detector, the DUNE horizontal drift TPC, will be instrumented with a wire-based Time Projection Chamber (TPC) and filled with 17 kt liquid argon mass (10 kt fiducial volume). It is planned that the DUNE experiment will take data for more than 20 years in order to fully explore the parameter space for CP violation in the neutrino sector [2].

The liquid argon TPC technology (LArTPC), first proposed in 1974[3], meets the required sensitivities for precision measurements of the neutrinos' properties and for investigating some of the possible proton decay channels. As shown in Fig. 2, charged particles passing through detector ionize the argon atoms, and the resulting electrons drift in the electric field to the anode wall on a timescale of milliseconds [4]. The anode consists of layers of active wires forming a grid. With 3 wire plane readout, time, geometry, and charge information are collected with excellent resolution.

There is a long history of development towards the use of large LArTPCs in neutrino experiments [5]. The location of readout electronics for a large TPC detector has a direct and far-reaching effect on the cryostat design, an indirect effect on the TPC electrode design, and a significant effect on the TPC performance. In 2010, it was pointed out by Brookhaven National Laboratory (BNL) scientist Veljko Radeka that cold electronics is the optimal solution for very large liquid Argon TPC [6]. With CMOS front end ASICs integrated with the TPC electrodes, the electronic noise is independent of the fiducial volume (signal cable lengths). The electronic noise is also much lower than with readout electronics at room temperature because at 77-89K, the charge carrier mobility in silicon increases and thermal fluctuations decrease with kT/e$^-$, resulting in a higher gain, higher g_m/I_D, higher speed, and much lower noise [7]. According to the physics simulations, the equivalent noise charge (ENC) of DUNE single phase far detector is required to be less than 1/9 of the expected worse case instantaneous charge arriving at the anode plane from a minimum-ionizing particle (MIP). This requires that the ENC for induction wires is smaller than 1000 e$^-$, a noise level that can only be achieved by cold electronics. In addition, signal digitization and multiplexing to high-speed links inside the cryostat result in large reduction in the quantity of cables and in the number of cryostat feed-through penetrations, giving the designers of both the TPC and the cryostat the freedom to choose optimal configurations.

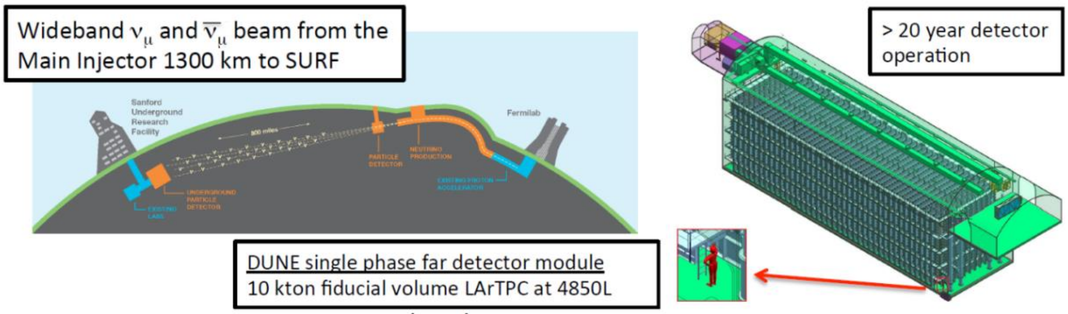

Figure 1. Left: concept of DUNE experiment. Right: DUNE single phase far detector.

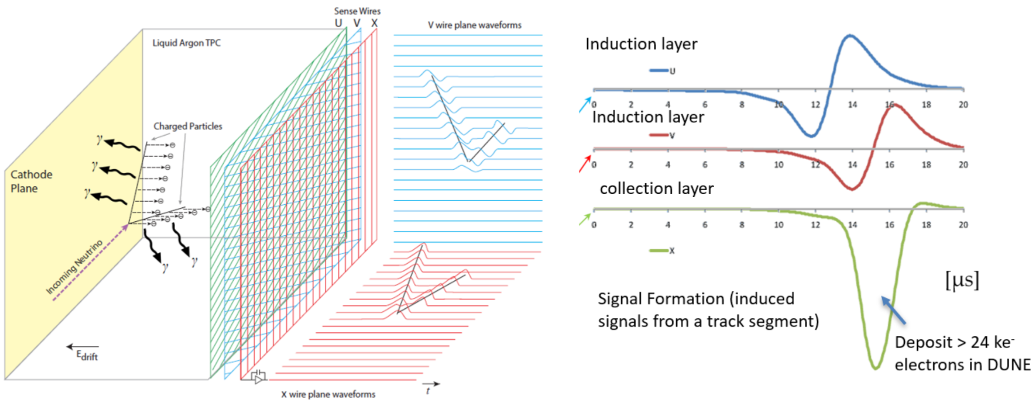

Figure 2. Left: the principle of LArTPC. Right: signal formation.

A significant amount of work by many institutions in the DUNE Collaboration has been directed at the development of the cold electronics for instrumenting large LArTPCs, culminating with the construction and operation of the ProtoDUNE single-phase (ProtoDUNE-SP) LArTPC. This was a crucial prototyping step in the DUNE development, as well as a significant experiment in its own right [4]. With a total liquid argon mass of 770 tons, ProtoDUNE-SP represents the largest monolithic single-phase LArTPC detector built to date. It is housed in an extension to the EHN1 hall at CERN, where the CERN Neutrino Platform provides a new dedicated charged-particle test beamline. As shown in Fig. 3, ProtoDUNE-SP consists of six full-size anode plane assemblies (APAs) plus three cathode plane assemblies (CPAs), corresponding to two 3.6m drift regions and 15,360 TPC sense wires. ProtoDUNE-SP was developed to be the final prototype for the first DUNE far detector module, and for this reason two periods of data taking are planned for. The first run of ProtoDUNE-SP started at the end of 2018 with a ~7-week test beam run including electrons, pions, protons and kaons in the 0.3 - 7 GeV/c momentum range, followed by cosmic rays data taking for more than one year. The first run of ProtoDUNE-SP has demonstrated that the performance of the currently available readout electronics meets or exceeds the DUNE specifications, in several cases by a large margin. A second period of data taking is expected in 2022-2023, after upgrading the detector to use the final full-scale prototype components that will be later installed in DUNE.

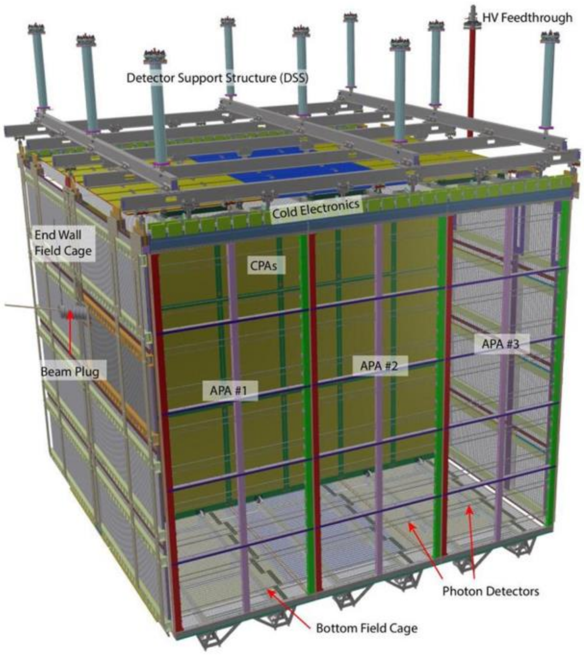

Figure 3. ProtoDUNE Single-Phase LArTPC schematic design

2. ProtoDUNE-SP Cold Readout Electronics

The ProtoDUNE-SP Cold Electronics (CE) system is shown in Fig. 4 [8][9]. The CE is mounted directly on the APAs and provides deadtime-less signal handling and transmission from the detector electrodes (indicated by the capacitive load left of the Analog Mother Board input) to the ProtoDUNE-SP Data Acquisition (DAQ) computers over optical fibers (represented by the arrows from the Warm Interface Board outside of the cryostat). All components and materials inside the cryostat, including power and data cables, have been qualified for operation in cryogenic liquids. CE consists of 120 Front End Mother Board (FEMB) assemblies for 15,360 TPC channels. Each FEMB contains one Analog Motherboard (AM), houses eight 16-channel analog Front-End (FE) ASICs providing amplification and pulse shaping [10], and eight 16-channel Analog to Digital Converter (ADC) ASICs for signal digitization. Both the FE and ADC ASICs are custom circuits designed at BNL implemented with the TSMC 180 nm CMOS process and operating at 1.8V, with very low power consumption. An Altera Cyclone IV FPGA, housed on a mezzanine card which is attached to the Analog Motherboard, provides clock and control signals to the FE and ADC ASICs. The commercial off-the-shelf FPGA is not designed for operation at cryogenic temperature; its performance in 77-89K was validated by standalone tests in LN_2 [10]. The FPGA also further serializes the 16 data streams from the ADCs into four 1.25 Gbps links for transmission to the warm interface electronics. Two sets of 7m cold cable bundles transport power, clock, control, and data signals between the CE flange and the FEMBs.

The ionization charge signals collected by the electrodes are very small which requires that the system noise of the LArTPC detector should be low enough to assure sufficient signal to noise ratio. In order to achieve a good noise performance, the APA, CE, feed-through and warm interface electronics with local diagnostics, must all be designed taking into account strict grounding and isolation rules [11]. An appropriate grounding scheme has been developed, following the experience from the ATLAS and MicroBooNE experiments. All the electrical connections (power and signal) from APA and CE inside the cryostat only lead to the signal feed-through with 7m cold cables. As a result, the feed-through is the only electrical connection of the APA frame to the cryostat.

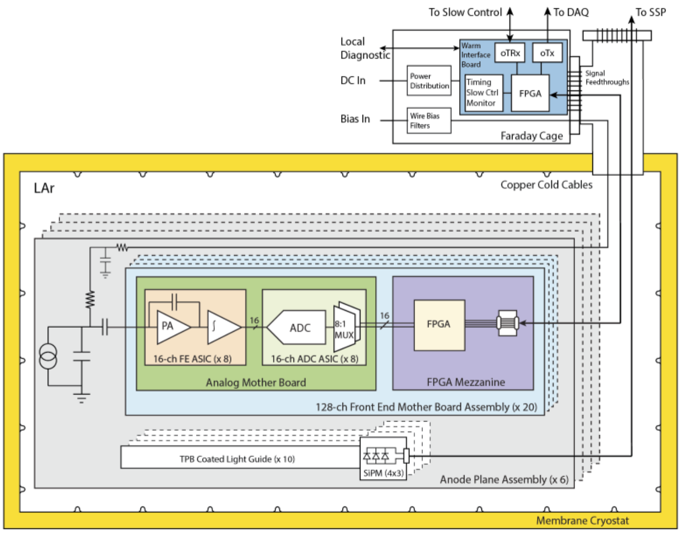

Figure 4. The ProtoDUNE-SP CE architecture. All components inside the Membrane Cryostat are operating submerged in LAr at 89K.

3. ProtoDUNE-SP CE Performance

A cold integration test stand is set up near the ProtoDUNE-SP cryostat in order to characterize the performance of the CE after installation on the full-size APAs. This test stand consists of a cold box that is sufficiently large to house a complete APA, allowing a vertical slice test of the APA and of the photon detectors. The cold box incorporates a full-size signal feed-through assembly and uses cables and readout electronics identical to the ProtoDUNE-SP readout system. In this setup, the APAs instrumented with the CE have shown very promising results, when tested at cold temperature. The noise measurement is shown in Fig. 5 together with the temperature inside the cold box. The temperature is measured by six RTD sensors located at different heights of the cold box. The top one, TT0206, which is closest to the FEMBs, records a temperature that is about 10 degrees lower than the temperature of the FE ASIC, which is measured by a sensor integrated inside the chip. At the lowest temperature reached in the cold box, about 159K on TT0206, the ENC of induction plane (U or V, 8m sense wires) is ~480 e^- and of collection plane (X, 6 m sense wires) is ~400 e^- for 2.0 µs peaking time [12]. It should be noted that this temperature is significantly higher than the temperature of liquid Argon (89K).

The design of a readout electronics system that operates in cryogenic liquids is much more challenging than that of a system operating at room temperature. Since the CE system is not accessible once it is immersed in LAr inside the cryostat, reliability issues must be considered carefully, requiring, for example, very detailed quality control (QC) procedures that are applied to all the detector components. Overall, the first run of the ProtoDUNE-SP LArTPC detector has been a success showing excellent performance [13]. The most important achievements for the CE are:

1. High yield. At the beginning of the first run, there were 99.7% of 15,360 of TPC channels active, where only 4 readout channels were inactive because of failures in the electronics. As of November 2019, after ~7 weeks of beam data-taking and ~11 months of cosmic rays data-taking, only 2 additional inactive channels were observed.
2. Low noise. 93% of the TPC channels are working with excellent noise performance (ENC < 800 e^-), well below the CE design requirements for the DUNE FD. Fig. 6 shows the promising noise performance achieved. The signal over noise (S/N) ratio for individual wire samples is measured using reconstructed muon tracks, achieving average S/N ratios larger than the DUNE requirements.
3. Good stability. There was no measurable degradation of cold electronics over a period of one year, proving the reliability and stability of the CE in LAr.

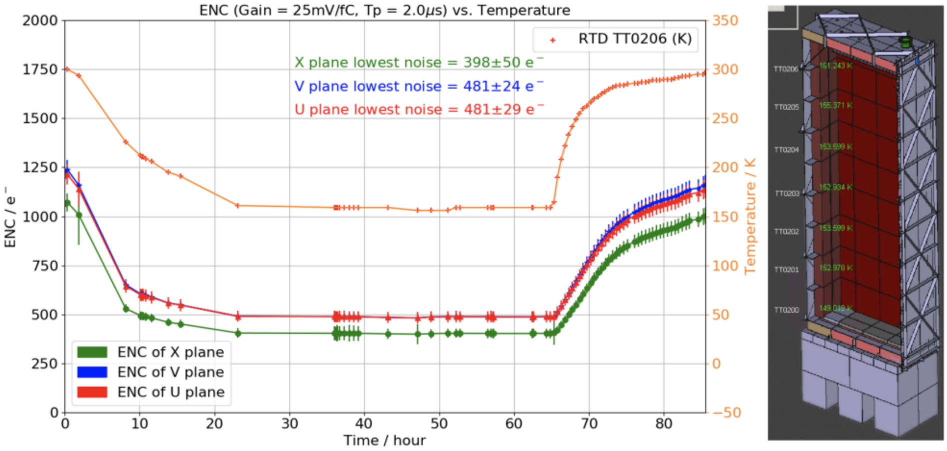

Figure 5. Noise measurement and temperature monitoring during the cold test of APA#2.

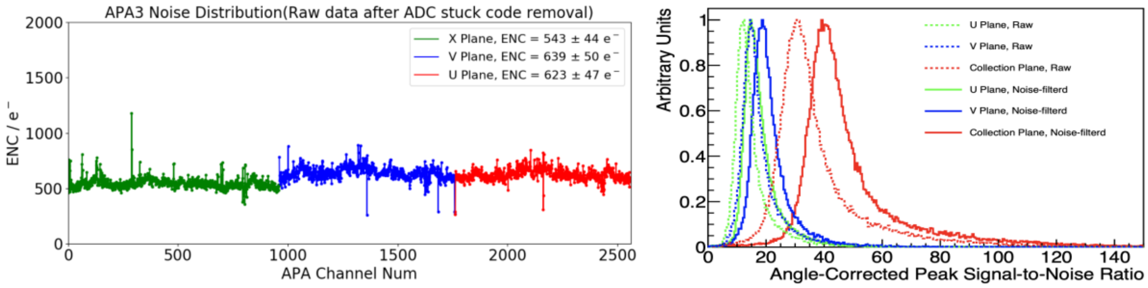

Figure. 6 Left: Noise distribution of APA3 inside cryostat. Right: signal over noise observed for reconstructed muon tracks on the three wires planes. For each plot, the signal over noise before (dashed line) and after (solid line) the offline noise filtering is shown.

4. Evolution of Cold Electronics towards DUNE

Even though the CE performance for the first run of ProtoDUNE-SP was excellent, there are a few issues that need to be addressed prior to using it in the 10 k-ton DUNE detector module. First, DUNE is expected to be operated for 20 to 30 years, and the biggest challenge to build detector components that will operate for 30 years without the possibility of any replacement and maintenance. CMOS devices in cryogenic temperature are affected by the Hot Carrier Effect (HCE), which can significantly reduce their lifetime [14][15]. The HCE can be mitigated with appropriate ASIC design rules to a level where it is not expected to contribute to failures over the planned DUNE lifetime. The first goal for DUNE is to replace the commercial components used in the first run of ProtoDUNE-SP (e.g. the FPGA) with custom cryogenic-enhanced ASIC solutions. Second, any design issues observed during the ProtoDUNE-SP QC and operations need to be addressed. For example, the FE ASIC suffers from a saturation effect and from yield issues at cryogenic temperatures, while the resolution of ADC is lower than needed. Third, the FEMB design should be simplified to ensure high yield during the fabrication and QC of the thousands of boards required for DUNE.

The first DUNE far detector module will be instrumented with 150 APAs consisting of 384,000 TPC channels which is 25 times the number of readout channels in the ProtoDUNE-SP TPC. To meet the requirements of high reliability and long lifetime, a monolithic FEMB with 3-ASIC solution has been developed, which is shown in Fig. 7. A new version of the 16-channel FE ASIC for amplification and pulse shaping, which is referred to as LArASIC, addresses the saturation effect and cold yield issues of the previous version ASIC used in the first run of ProtoDUNE-SP. A new 16-channel 12-bit ADC ASIC operating at 2MHz, referred to as ColdADC, has been developed. This ASIC is designed in the TSMC 65nm CMOS technology and has demonstrated in laboratory tests ADC functionalities with good static and dynamic performance at both room and LN_2 temperatures [16]. A 64-channel control and communications ASIC, referred to as COLDATA, also designed using the TSMC 65 nm CMOS technology, has demonstrated all major interfaces, including receiving data from ColdADC, distributing timing and slow control commands to ColdADC and LArASIC, and data transmission to the warm interface board at both room and LN_2 temperature. The gain of each channel of the FE is calibrated using an on-chip test capacitor (~183 fF and stable at cryogenic temperature) for each channel and a pulse generated either by an on-chip 6-bit DAC or an external pulser. During tests of the FEMBs prior to their installation on the APAs the capacitance of the sense wires (~150pF in LAr) is emulated using a 150pF MICA capacitor applied at the FE input. The noise of the readout chain is measured at both room and LN_2 temperatures. The measured ENC decreases significantly at cryogenic temperature. At LN_2 temperature, the measured noise is around 500 e^- for the 1μs peaking time, which is comparable with that obtained with the FEMB used in the first run of ProtoDUNE-SP.

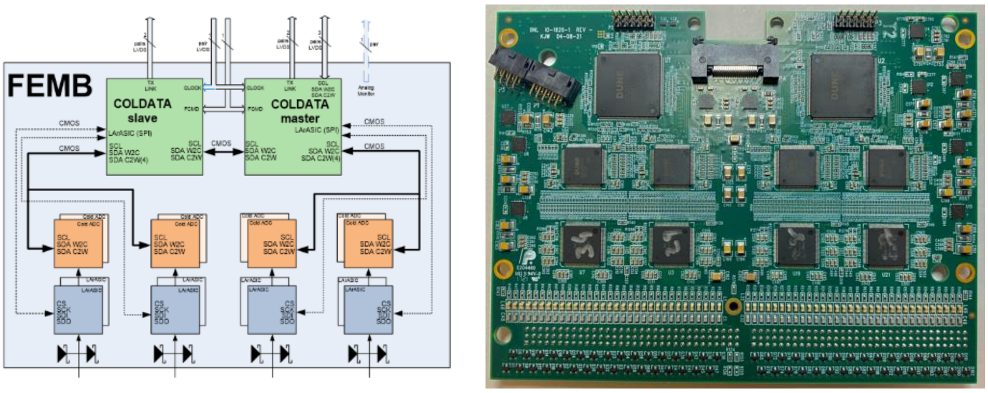

Figure. 7 Left: block diagram of FEMB. Right: the monolithic FEMB.

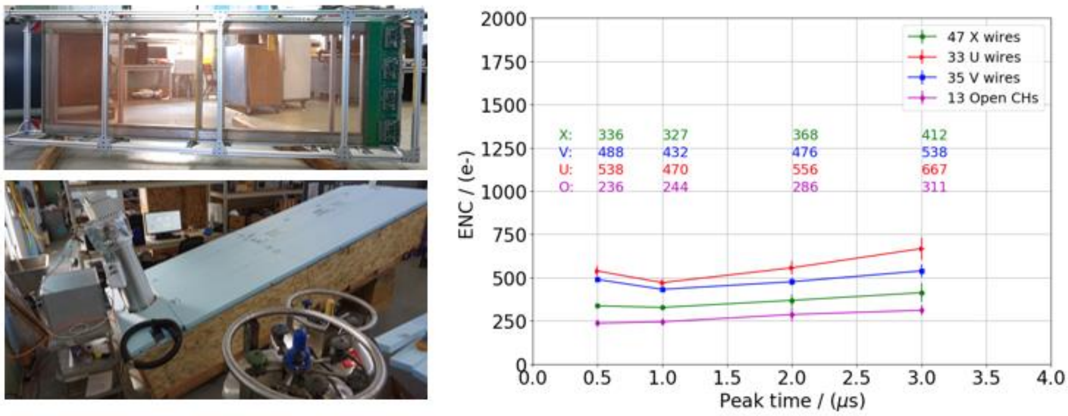

Figure. 8 Top left: the 40% APA. Bottom left: 40% APA integration test with liquid nitrogen at BNL. Right: measured noise performance

An APA integration test stand (called the 40% APA) has been built at BNL to practice the integral system design concept. As shown in Fig. 8, the APA sense area is about 2.8 m^2 with 2.8m X-plane collection wires and 4.0m U- and V-plane induction wires, which is ~45% of the DUNE full-size APA (6.0m × 2.3m). This APA has 1,024 sense wires, which require 8 FEMBs. The 40% APA follows the grounding and isolation rules developed for ProtoDUNE-SP. As shown in Fig. 8, the noise performance of the 40% APA with 3-ASIC FEMBs submerged in LN2 is quite promising. The ENC of induction plane (U or V) is ~400 e^- and of collection plane (X) is ~340 e^- for the 1μs peaking time. Based on the test results, the expected noise for the ProtoDUNE-SP induction plane is ~600e^-, while for the collection plane it is ~500 e^-.

5. Conclusion

Readout electronics developed for low temperatures (77-300K) is a key technology for large liquid detectors for neutrino experiments. The deployment of cold readout electronics has been validated in the ProtoDUNE-SP detector at the CERN Neutrino Platform. Confidence towards the construction of the DUNE 10 k-ton LArTPC detector has been gained due to the excellent performance delivered during the commissioning and operation of the first ProtoDUNE run. To meet all DUNE's needs, especially to achieve the long lifetime and high reliability, a simplified CE readout unit, the monolithic FEMB with three custom cryogenic ASIC has been designed. The 40% APA integration test performed at BNL projects the promising performance that the DUNE LArTPC can get. As the final validation for DUNE far detector construction, the 3-ASIC monolithic FEMB has been chosen to instrument ProtoDUNE-SP for the second run that will take place in 2022.

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