A FAST METALLIC CONTACT CLOSING SWITCH FOR THE FDX EXPERIMENT

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1 SUMMARY

The Fast Discharge Experiment (FDX), which is described in a companion paper, requires for current initiation a switch capable of carrying a peak current of $1.9\ 10^6$ kA with an initial rate of rise of 3 kV/μs. These requirements preclude a conventional making switch. The solution chosen uses electromagnetic repulsion to drive a movable contact which in the closed position metallically bridges two stationary electrodes. Once closed, the device has very small internal resistance and a minimum of inductance. The design is described, the application in the FDX experiments is shown and the predicted performance is compared with actual test results.

2 INTRODUCTION

Many future high energy physics applications, particularly controlled thermonuclear experiments will require very large power pulses. The anticipated requirements are well above existing capabilities, and economical power supplies must be provided. Fast discharging homopolar machines, capable of inertially storing large amounts of energy (at least 50 times more per unit volume than a static capacitor) and then electromagnetically converting the energy in about one millisecond, are an attractive alternative. These machines, at a cost of about two cents (US) per J, are substantially less expensive than capacitor banks, which cost about 25 cents per J.

The Center for Electromechanics at the University of Texas at Austin has researched fast discharging homopolar machines since 1974 and began the design of a Fast Discharge Experiment (FDX) in September of 1975. FDX, (Gully et al 1977), is a 365 kJ, 200 MW generator when discharged from 1500 rad/s in a short circuit configuration. The shortest anticipated time for the current to peak is approximately one millisecond.

FDX is the first fast discharge homopolar machine to be built and tested and will provide original experimental data on parameters critical to future machine development. A successful discharge is an important step in the acceptance of these machines as a new source of pulsed power.

FDX is designed to investigate performance limits; therefore many components are not state-of-the-art. In particular, a making switch capable of carrying a 2 MA discharge is required. Large brush losses and the timing sequence call for a fast actuation time and an extremely fast contact engagement.

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3 DESIGN CONSIDERATIONS

The machine has a low source impedance of 15.4 nH and 18 μΩ. The terminals are coaxial cylinders with a median diameter of 35.5 cm surrounding the rotational axis of the machine. A perfect switch would short out the entire circumference of this coaxial conductor. Due to conditions of access, this ideal condition could not be satisfied; however, an arrangement of four radially placed switches was found which combines good access to the switches with a minimum of added impedance.

The need to keep the voltage drop to an absolute minimum made the metal to metal contact mandatory and ruled out arcing devices such as ignitrons or solid dielectric switches of the exploding wire type or the chemical explosive variety. A pneumatically driven or spring actuated switch might have been satisfactory since closing time is not of paramount importance. However, the geometry of the machine dictates the use of a minimum of four switches, which in order to avoid magnetic imbalance in the machine itself during discharge, have to be closed with as little jitter as possible. Considering the rate and rise of the current, a difference in timing of say 100 μs between two switches, could create an imbalance in the current of nearly 300 kA. This would invalidate the experiment and the resulting forces would endanger the machine. These performance requirements make metal-to-metal switches based on the magnetic repulsion principle particularly attractive.

The principle of magnetic repulsion has been used commercially since the early sixties for magnetic metal forming (Brower, et al 1968). As a result, coil technology has been developed and substantial knowledge of the behavior of metals under these conditions has been gained. The principle has also been used in a similar switch application with a different geometry and for a $\int i^2 dt$ value approximately 1/12 of that contemplated in the FDX switch (Bleys, et al 1975).

The basic circuit of the magnetic repulsion system is shown in Figure 1. It consists of a capacitor bank, a switch (usually an ignitron), a transmission line, a repulsion coil and a movable contact. To be effective, the moving part must be a good conductor and tightly coupled magnetically with the repulsion coil. In such a circuit the current in the coil, and with it the magnetic field intensity, take the form of an exponentially damped sinusoid (at least during the time before any appreciable motion of the system occurs). The pressures generated are proportional to the square of the magnetic field intensity. In practice it is quite feasible to build coils having a good life expectancy and capable of peak pressures on the order of 70 MPa (10,000 psi).

The anticipated shape of the discharge current is shown in Figure 2. The peak current will be 1.88 10^6 A; $\int i^2 dt$ equals 6.2 10^9 $A^2 s$. The rate of rise of the current at the onset of the short circuit is 2900 A/μs. These are the significant design parameters for the making switch. The first number determines the dynamic forces on the contacts. The second is an indication of the thermal load, especially of the contact points; and the third number determines the minimum rate at which the contact resistance must decrease in order to avoid sparking. It also determines the minimum jitter admissible between several switches. The open circuit voltage before circuit initiation is 104 V. This determines the insulation requirement for the open gap and thus the contact separation. The low open

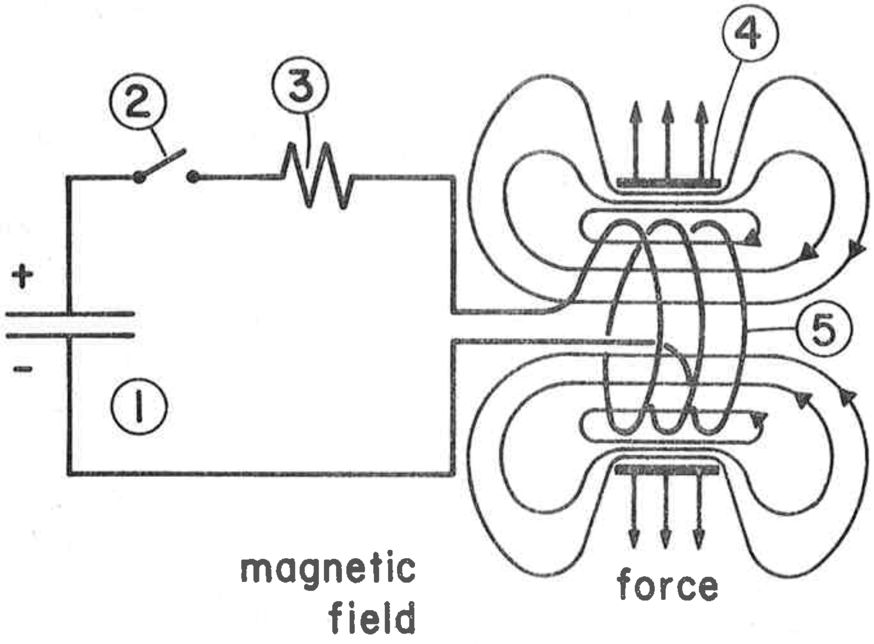

Figure 1. Principle of Magnetic Repulsion System

1	Capacitor	4	Repelled load (ring, moving contact)
2	Switch (eg. ignitron)		
3	Resistance of circuit	5	Drive coil

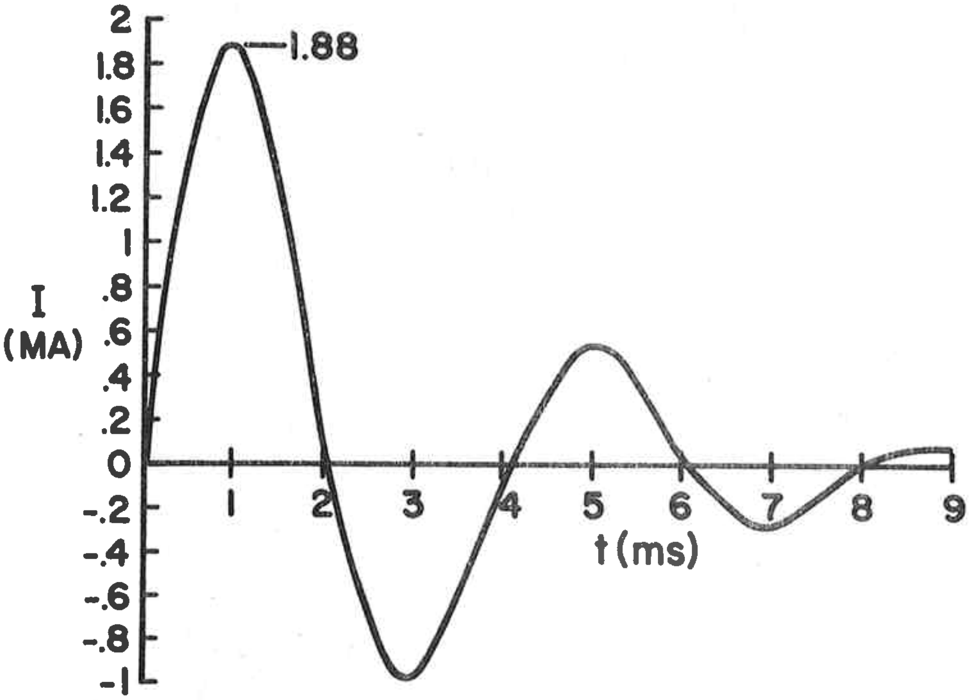

Figure 2. FDX Short Circuit Output Current (from 1500 rad/sec)

circuit voltage of 104 V also tells us that the possibility of prestrike is not a consideration in this particular design.

4 SWITCH ASSEMBLY

The overall assembly shown in Figure 3 shows one switch unit in the open, ready-to-close state. The switch consists of a stationary part arranged coaxially containing the coil and a contact sleeve which can be removed

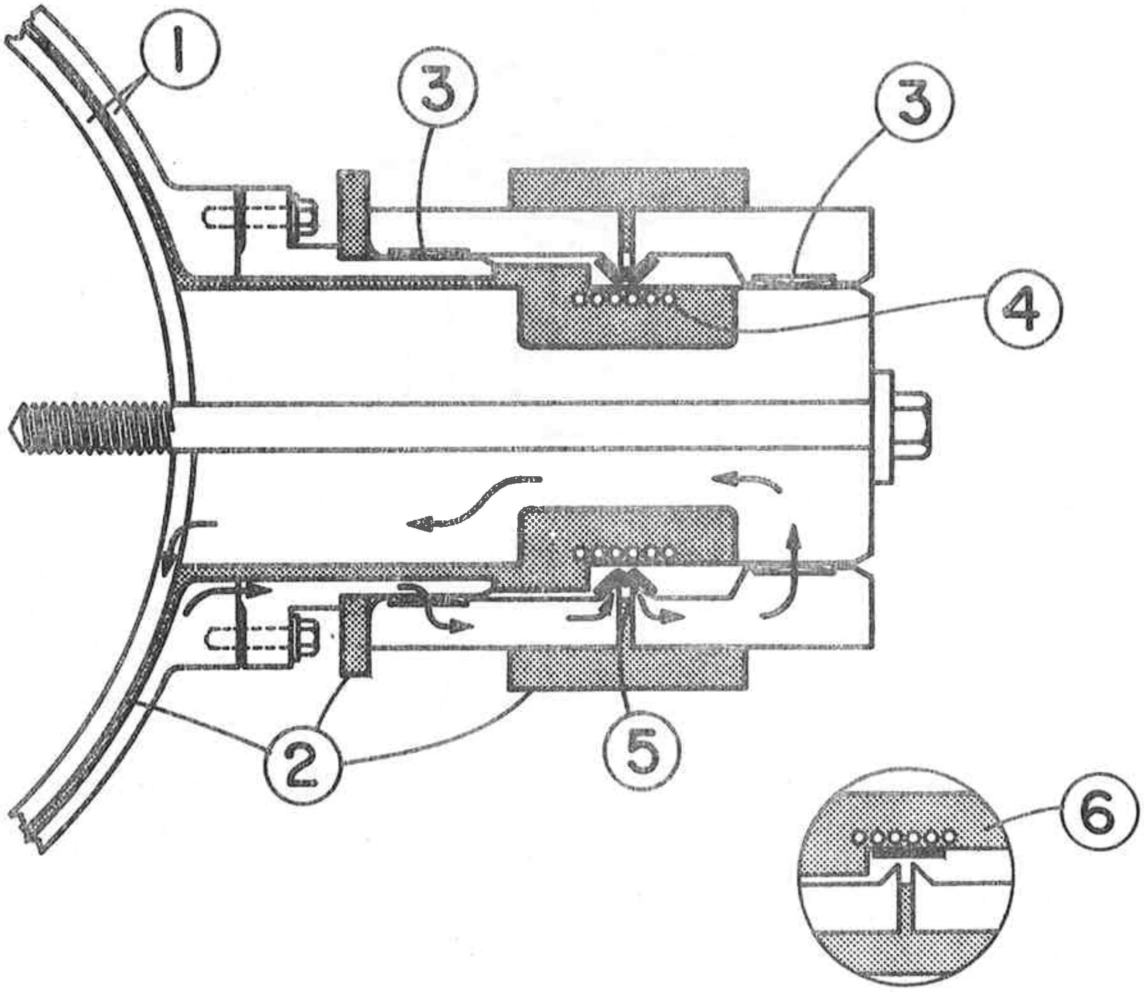

Figure 3. Making Switch Assembly in Closed State and (insert) in Open State.

1 Machine terminals
2 Insulation
3 Sliding contact rings
4 Driving coil
5 Contact ring in closed position
6 Contact ring in open position

in order to permit loading of the contact ring. The contact sleeve connects to the stationary part by means of two specially segmented spring contacts. It contains the stationary contact proper. The contact ring closely surrounds the driving coil. When the coil is pulsed (to close the switch) the ring expands rapidly, wrapping itself over the open switch gap in the fashion shown. To rearm the switch for a subsequent test, the whole contact sleeve is removed. The spent contact ring is collapsed, a new ring is loaded in place and the contact sleeve is slipped back into position. The switch is now ready for another operation.

5 POWER SUPPLY AND FIRING SYSTEM

Figure 4 shows the overall system. The capacitor bank is divided into four sections, each powering one switch. The capacitors are charged by a common power supply and controlled by a common firing circuit. Each section of the bank has a capacitance of 170 μF and can be charged to 7.5 kV corresponding to an energy of 4.8 kJ.

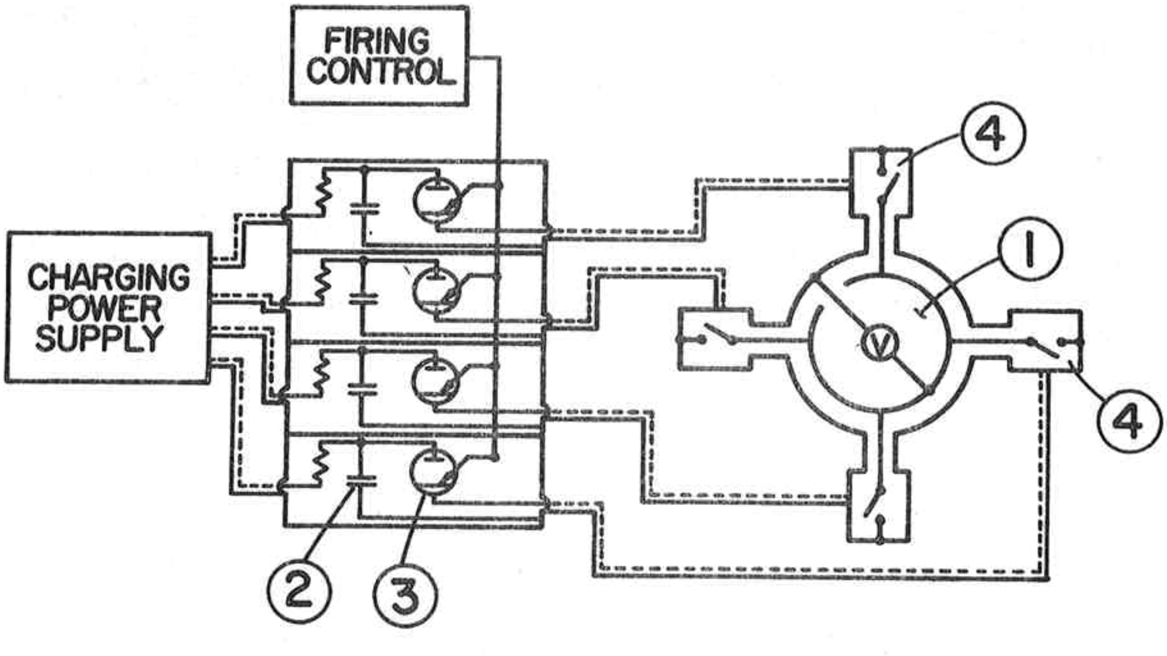

Figure 4. FDX Closing Switch System

1	FDX Machine	3	Ignitron
2	Capacitor	4	Closing switch

6 CALCULATED PERFORMANCE

A six-turn driving coil as shown in Figure 3 has an inductance of 1.9 μH with the contact ring in place. With a capacitance of 170 μF this results in a basic discharge frequency of 8.9 kHz; and making reasonable assumptions for damping results in a first current maximum of 40 kA corresponding to a pressure of 45.5 MPa (6,600 psi) on the ring.

Before any appreciable motion of the ring occurs, the inductance of the coil can be considered constant. The pressure will then build up as shown in Figure 5. For a first approximation the pressure required to stress the ring to the yield point can be considered constant. The magnetic pressure in excess of the yield pressure is available to accelerate the ring outward toward the contacts. An outward motion on the order of 1 mm in approximately 25 μsec and almost 2 mm of motion in 30 μsec is expected. Velocities at these points will be 150 m/s and 200 m/s respectively. Since the voltage over the open gap is at the most 104 V, a separation of 1 to 2 mm is adequate. (It should be noted that the same switch arrangement could be used for much higher voltages by either filling the cavity with a dielectric gas or by using a solid insulation and permitting the contacts to cut through upon making.)

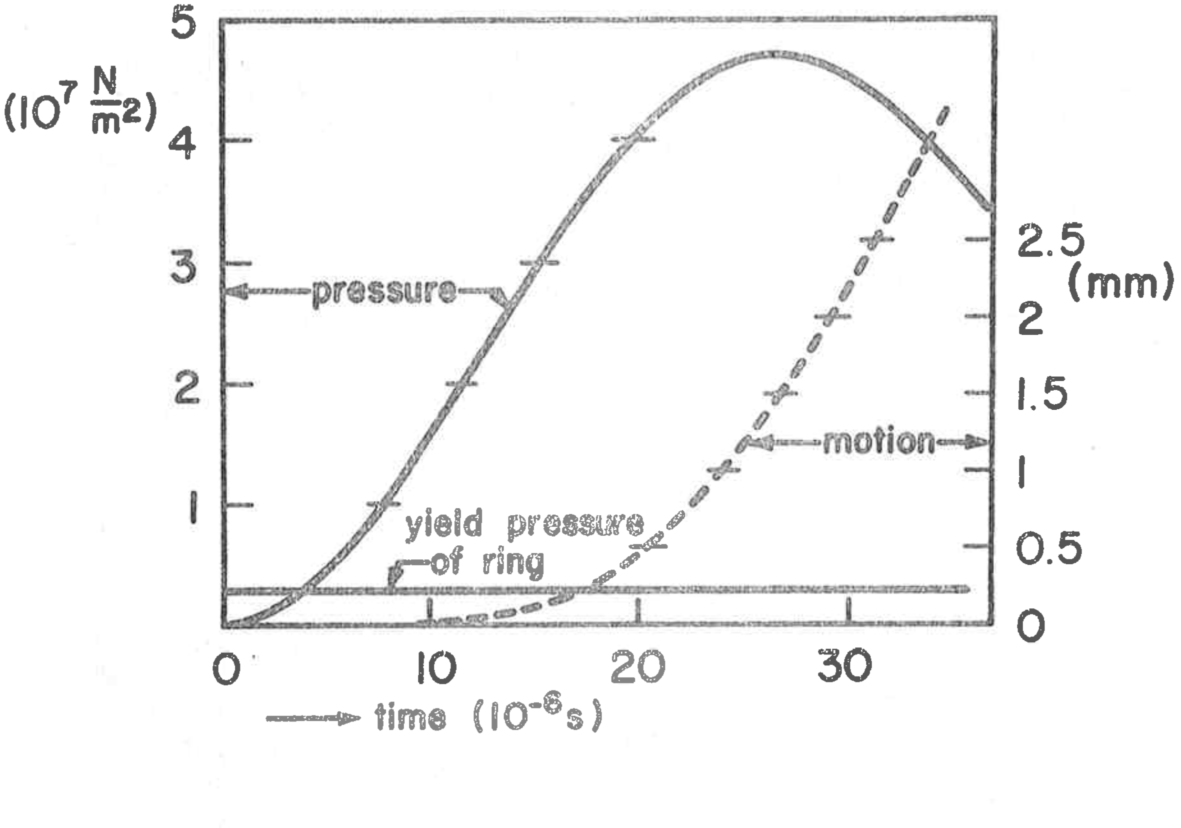

Figure 5. Magnetic Pressure vs Distance of Contact Ring from Coil

The closed contact will experience an additional heating of 60°C during passage of the discharge current. This adds to the heat produced by the induced current of the driving field and heating of the material due to the yielding of the band. The discharge current will help keep the contact closed. The magnetic pressure of the discharge current at the time of peak current is $1.55\ 10^6$ N/m^2 (225 psi). The closed short circuiting switch will have an inductance (at 250 Hz) of L = 20 nH and a resistance of 16 μΩ as seen from its mounting base. For four switches in parallel this will then add 5 nH and 4 μΩ to the short circuit loop.

7 EXPERIMENTS PERFORMED TO DATE

In order to test the switch's capability to close in the predicted time and to handle an appropriate voltage and an adequate rate of rise of current, the first switch produced was tested in a simulated circuit in which the switch had to withstand the charging voltage of the capacitor bank and initiate the discharge of that bank. Figure 6 shows a typical oscillogram in which the switch withstood, prior to closing, a voltage of 1100 V; made contact within 33 μs after closing signal and initiated a current with a rate of rise of $12.7\ 10^{12}$ A/s which is far higher than the design value. The peak current and the heat effect ($\int i^2 dt$) were, of course, considerably lower than the design values. These two quantities are very amenable to calculations, and there is no doubt that the switch will perform per specification.

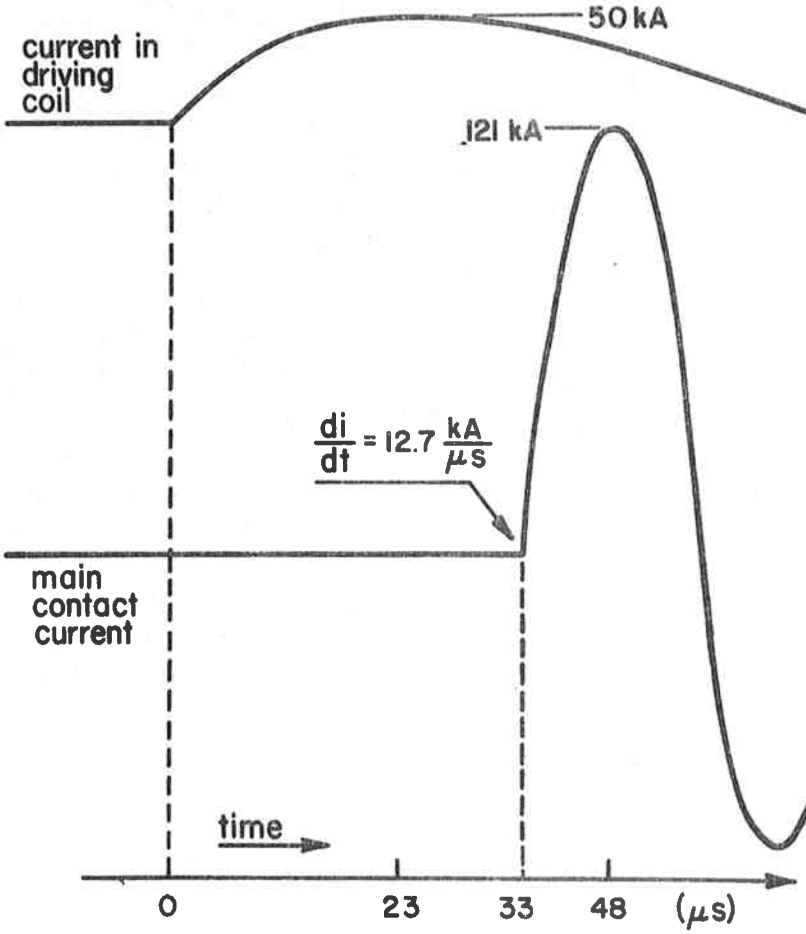

Figure 6. Closing Test; Oscillogram.

8 CONCLUSIONS

The principle of the switch described permits the construction of making switches with actuating times one or two orders of magnitudes shorter than the conventional fast mechanical switches and current and charge carrying capabilities far in excess of spark gaps and other gaseous discharge devices. Apart from the current applications, they have a usefulness as emergency crowbar switches and protective short circuiting devices.

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