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"Plastic" Axial Flux Machines: Design and Prototyping of a Multi-Disc PM Synchronous Motor for Aircraft Applications

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Abstract - After more than 100 years of development, rotating electric machines are a mature industrial product. Nevertheless, improvements are still possible for specific applications, and it is likely that the major evolution will be promoted by new materials and unconventional structures. Till now, plastic materials are an infrequent choice for the electric machines structural parts, but pioneering applications, such as aeronautical components, let some technological scouting: a low-weight/high-efficiency plastic axial flux motor for a solar flying platform is presented as an example of combined new-material/new-geometry development. The basic design aspects and the prototyping choices are presented and discussed together with the first experimental results.

Keywords: Brushless machines, plastic materials, axial flux, ironless

1. Introduction

The rotating electric machines are a rather mature and pervasive industrial product; nevertheless, optimization and improvements are still possible for motor designs dedicated to specific applications, and it is likely that the major evolution will be promoted by the availability of new materials. Analyzing the literature about unconventional motor structures over the last 10-15 years, it is evident that the most interesting proposals have a common element: the three-dimensional flux path [1] such as concentrated coils motors, transverse flux motors, and axial flux motors. In these motors, the magnetic circuit cannot be completely described in a two-dimensional plane as for the common industrial motors. Due to their magnetic circuit geometry, the unconventional "3D motors", usually, suffer a key problem: the laminated iron technology is not suitable for the magnetic core and mechanical structure.

Together with the "solid" machined or "printed" iron cores, the ironless, or almost ironless, magnetic circuits allow to get rid of the laminated iron difficulties. The practical feasibility of these solutions is based on the availability of new materials (at least, new in the electric machines production) for the reduction or elimination of ferromagnetic material.

At present, plastic material is a rather infrequent choice for the structural parts of electric machines: the costs, as usual, are the determining factor. Nevertheless, pioneering applications, such as aeronautical components, offer the opportunity for technological scouting: the authors propose a low-weight/high-efficiency plastic axial flux motor prototype for a solar flying platform as an example of combined new-material/new-geometry development.

2. Machine Design

2.1 The application

HeliPlat'$^{©}$ is a stratospheric unmanned aircraft [2] proposed for use as telecommunication platforms in the 'HeliNet Project', funded by the Information Society Technologies Programme (IST), within the European Union Fifth RTD framework. 'HeliPlat'$^{©}$ employs eight propellers, each of them is directly driven by a single motor, supplied by a solar cells - fuel cells energy system [3].

The aircraft must be able to take off by itself, climb to the destination altitude (17÷25 km) and then keep a constant altitude in a turning flight to achieve a geo-stationary position: full power is required during take off and climbing to the target altitude, but only about ¼ of the full power is enough to maintain level flight. Since there are no reduction gears between the motor and the propellers, the application requires a low-speed/high-torque duty.

2.2 The specifications

The most qualifying characteristics requested to the propulsion motors are:

- the best specific torque;
- the high efficiency overall the wide power range;
- the dimensions/shape compatible with the allocation constraints inside the wings (Fig. 2).

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Since the motor is fixed to the aircraft structure made of carbon fibre, the maximum motor external temperature is limited by the maximum temperature that the carbon fibre can withstand without loosing its mechanical properties.

The motor performance comes mainly from the take off working condition (Table I): full load, full speed (almost), high ambient temperature and high air density.

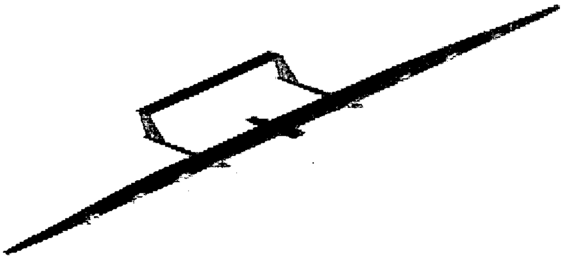

Fig. 1 Heliplat© Stratospheric Platform (Courtesy of DIASP).

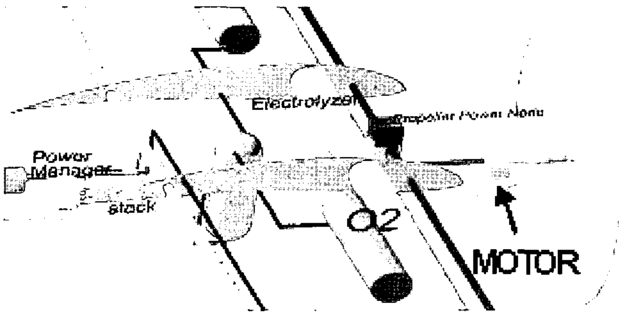

Fig. 2 HeliPlat© motor allocation (Courtesy of DIASP).

Table 1 motor technical specifications

Power (full load)	2,250 [W]
Torque (full load)	21.5 [Nm]
Speed (max)	1,000 [rpm]
DC Bus Rated Voltage	360 [V]
Outer diameter	≤ 300 [mm]
Overall length	≤ 150 [mm]
Max. chassis temp.	100 [°C]

Finally, considering also the extreme environment conditions (Table II), there is no doubt that a dedicated machine design is needed to satisfy the challenging application requirements.

Table 2 environmental conditions

Max ambient temperature	+ 35 [°C]
Min ambient temperature	- 55 [°C]
Max air pressure	1 [atm]
Min air pressure	1/12 [atm]

2.3 The basic design choices

The following guidelines have been followed in developing the motor design:

- the permanent magnets brushless motors have been considered since these motors allow the highest power density and efficiency;
- the "iron-less" magnetic circuit has been adopted in order to reduce the iron losses which, being almost constant at a given speed, affect the efficiency when the motor operates at low load;
- the multi-disc topology has been selected because it gives multiple air-gap surfaces, thus compensating the low airgap flux density due to the "ironless" magnetic path;
- the plastic and composite materials have been adopted for the structural parts to get low weight and no eddy currents in the mechanical components.

Some analyses have been performed to compare the plastic multi-disc axial flux structure with a "conventional" design based on an iron radial flux magnetic circuit to confirm the claimed potential advantages [4-6]. Then, the preliminary design has resulted in the "iron-less" "plastic" 16 pole PM Multi Disc Axial Flux motor (PM MDAF) depicted in Fig. 3.

3. The Machine Structure

The multi-disc motor structure consists of 4 rotor discs interleaved by 3 stator discs (Fig. 4).

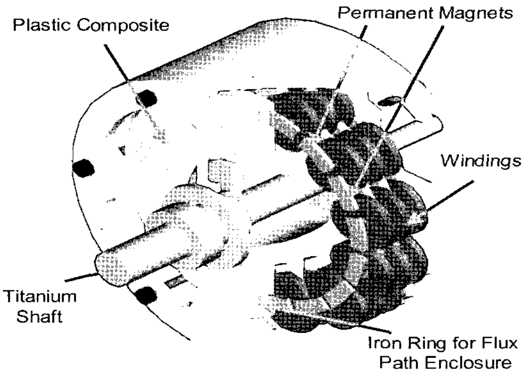

Fig. 3 Multi Disc Axial Flux Machine 3D section

The rotor of this machine is made of non-magnetic plastic discs that provide the support structure for an array of permanent magnets of alternating polarity, forming a 16-pole motor (Fig. 5.a). An iron ring is located in the two end rotor discs; it rotates with the magnets and closes the flux path. The permanent magnets have the same circumferential position on each disc. The flux goes along the machine axially through a line of magnets; then it goes circumferentially in the end iron ring to the next pole and finally comes back along the machine through an adjacent line of magnets, as shown in Fig. 4.

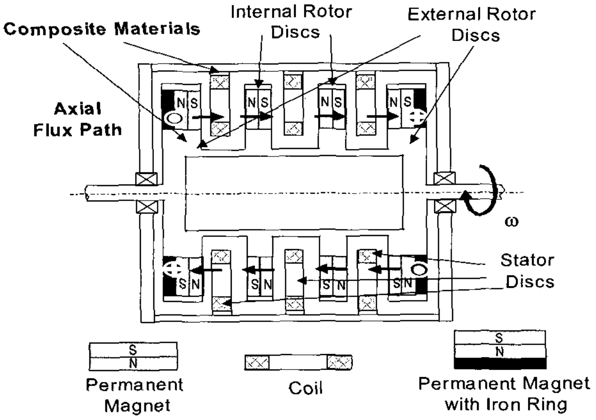

Fig. 4 Axial Flux Machine Structure

The stator discs interleave the rotating magnet discs. These are again made of plastic and provide the support matrix for a set of stator coils. The construction is therefore modular and one module consists of a rotor and a stator disc (Fig.5).

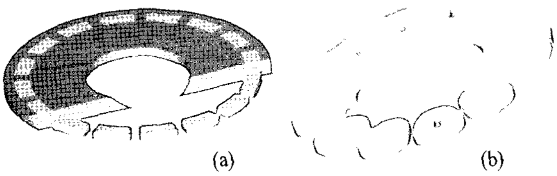

Fig. 5 Motor module - rotor disc (a) and stator disc (b)

The iron-less disc machine structure leads to air-gap slotless concentrated stator windings that should ideally be planar without coil end winding crossovers. Among the different possible arrangements, 'concentrated' type windings have been chosen for the relative simplicity of manufacture; in order to improve the winding factor, the second harmonic of the m.m.f. is used instead of the first harmonic. As a consequence, the three coils of the winding occupy the same arc as 4 poles (3 coils – 4 poles). In this way, the winding factor produced is 0.716, which is rather high for concentrated windings. The concentrated windings have a relatively poor copper exploitation due to the long end connections but, on the other hand, there is room for copper due to the absence of iron, hence the copper losses can be kept quite small.

4. The Materials

The basic components of the multi-disc motor can be listed under two main categories: electromagnetic parts and structural parts.

The electromagnetic materials are well known and few comments are needed:

- Copper - since the airgap windings see the main airgap flux, the eddy currents in the copper strands are not negligible; for that reason the conductor should have the smallest possible diameter compatible with the manufacturing and fill factor constraints.
- PMs - Neodymium Iron Boron PMs have been selected. Large thickness is required due to the high magnetic reluctance path.
- Iron - conventional Fe-Si iron can be adopted for the flux closure rings. The iron losses in the end discs, rotating at the synchronous speed, are rather low, since they are due to small space harmonic fluxes.

The structural materials adopted for the motor construction are completely unconventional in the electric machines manufacturing. The low maximum temperature (about 125°C) and the low maximum speed (1000 rpm) are key factors in the materials choice. Plastic and carbon fibre structural parts have been adopted to reduce the weight and the power losses. In particular:

- Carbon fibre - the stator chassis and the rotor shaft are made of carbon fibre. The rotor shaft has an increased diameter after the bearings to minimize the rotor disc misalignments and to get an internal airflow along the hollow shaft for a more effective cooling.
- Plastic material - stator and rotor discs are made of Ketron PEEK™. Ketron PEEK™ is a relatively new plastic having mechanical and thermal characteristics (Table III) that are the best trade-off among the different aspects. In particular, it maintains relatively good mechanical characteristics up to 150°C and, at the same time, has a sufficient thermal conductivity and good properties regarding moisture absorption, steam resistance and machinability.

The rotor discs are more mechanically stressed respect to the stator discs; in particular, the two external rotor discs must stand an important axial force due to the unbalanced magnets attraction. Hence these discs are:

- thicker than the internal rotor discs where the forces are almost completely deleted by the symmetry;
- made of glass fibre reinforced composite material having more stable mechanical characteristics at high temperature, but higher density and more difficult machinability.

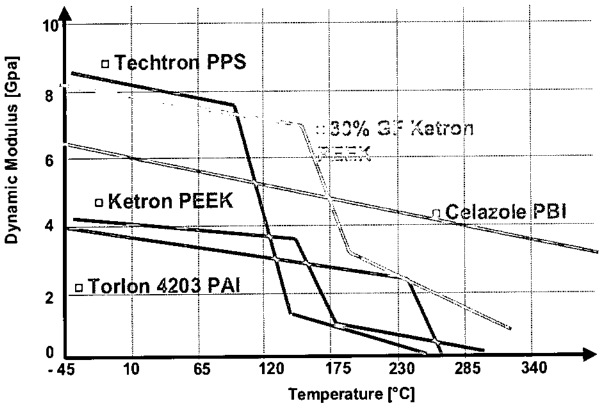

Fig. 6 Dynamic modulus (index of the capability of the material to limit deflection under load) of structural plastics.

Table 3 ketron peek™ properties

Property	Ketron PEEK™	Glass fibre reinforced Ketron PEEK™
Overall Chem. Resist.	Very Good	Very Good
Moisture Absorption	Very Good	Very Good
Steam Resistance	Good	Good
Wear Resistance (dry)	Very Good	Very Good
Specific Weight [kg/dm^3]	1.31	1.51
Cont. Service Temperature	(250°C)	(250°C)
Heat Deflection Temp. under Load	(160°C)	(230°C)
Coeff. of Linear Thermal Expansion [K^{-1}]	5.00E-05	3.00E-05
Thermal Conductivity [W/mK]	0.25	0.43
Dynamic Modulus [GPa] @100°C	≈4	≈7.5
Machinability (1=easy 10=very difficult)	5	7

5. MACHINE DESIGN

The machine design has been developed integrating the traditional approach and FEM analysis [7], yielding the results shown in Table IV. The estimated efficiency is above the 90 % over the working range. The estimated total weight is about 14 kg considering bearings, plugs, etc. (Table V).

Table 4 dimensions of the designed machine

Axial length	154 [mm]
Axial length (active part)	86 [mm]
External diameter	306 [mm]
Airgap	1.0 [mm]
Magnet discs thickness	8 [mm]
Winding discs thickness	7 [mm]

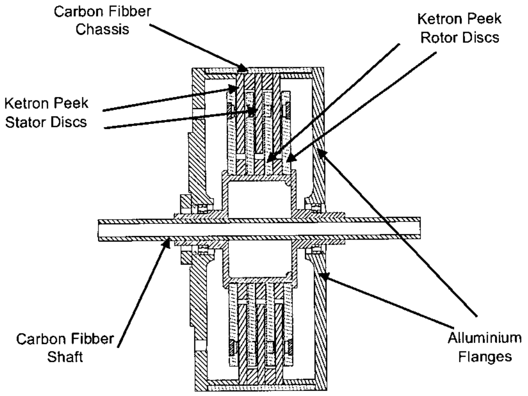

Fig. 7 Axial section of the multi-disc motor.

Table 5 Weight of the motor materials

Electromagnetic Material weights (kg)	
Copper	3.2
Iron	0.7
PM	1.5
Total	5.4
Structural Materials weights (kg)	
Aluminium	4.0
Plastic discs	2.5
Carbon fibre	1.0
Total	7.5

6. MACHINE PROTOTYPING

The prototype (Fig. 8) has been realized facing the problems related to the unconventional materials and geometry; all the parts had to be realized ad hoc from different suppliers and then assembled.

Some technical and economical constraints have lead to some differences between the prototype and the original design. In particular, the rotor and stator units (the module) basically correspond to design, but the chassis and the shaft have been realized using conventional materials (aluminium for the chassis and titanium alloy for the shaft), also to allow the easy mounting on the test bench: the prototype has to prove the basic design ideas but, it will be not embedded on the aircraft.

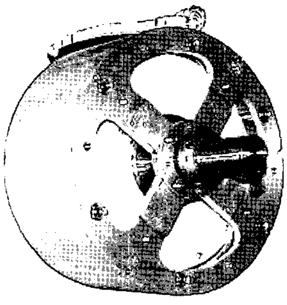

Fig. 8 Multi-Disc Axial Flux Machine Prototype.

The stator consists of three 290 mm diameter discs containing the coils. Each stator is divided into two half discs so that the rotor can first be completely constructed and balanced and then the stator discs can be inserted. The strands of wire forming the coil conductors have been made of small diameter wire to reduce the eddy currents, induced by the main air-gap flux. The final choice of the 0.4 mm wire diameter is the trade off between low eddy current losses and the ease of hand manufacturing the coils (Fig. 9).

The stator coils are glued into the plastic stator half discs that provide the mechanical support. Medium viscosity glue must be used and high precision gap is required for its application on the Ketron PEEK™ surfaces. Since the heat sources of the motor are concentrated in the coils, the glue must withstand high temperatures. The glue used for the assembly of the stator discs belongs to the two component Polyurethane family that can operate continuously up to 120°C.

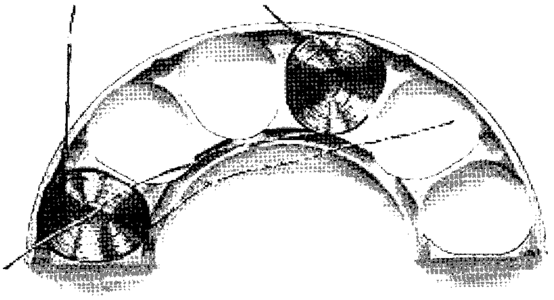

Fig. 9 The half-stator disc and the coils.

The rotor permanent magnets have a typical B_{rem} of 1.2 T and a coercitive force of 890 kA/m, can withstand a maximum working temperature of 150°C and have zinc coating. The magnets have been made with stepped sides to give better fixing into the plastic discs; this solution brings to a more reliable assembly of the discs because the integrity is not based entirely on glue joints (Fig. 10). To join the magnets to the two plastic discs a two-component low-density epoxy resin has been used.

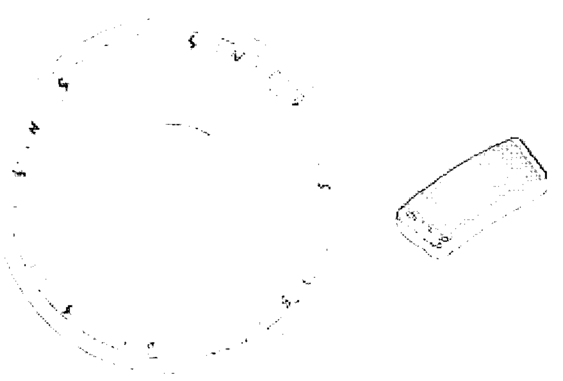

Fig. 10 Rotor Disc and an NdFeB permanent magnet.

In the two external rotor discs the NdFeB permanent magnets were inserted together with an iron ring for the flux closure. The discs are made of glass fibre reinforced Ketron PEEK™ to withstand the unbalanced attractive action of the permanent magnets. To further limit the disc deformation due to the attractive action of the permanent magnets, the shaft has been made of titanium alloy with a two-diameter structure (Fig. 11). In the prototype, the estimated force of about 700N has not lead to significant deformations.

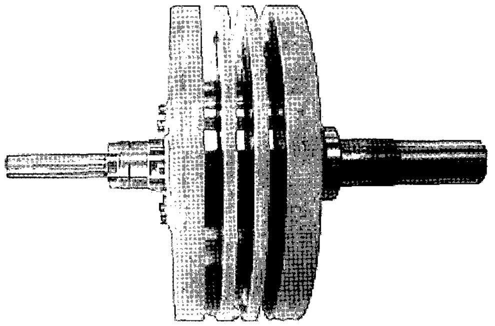

Fig. 11 Rotor assembly.

The plastic discs have been realized by machining the material; the cutting process generates some internal stress in the material bringing to a relatively poor planarity. From the initial design, the electromagnetic structure has been slightly changed, increasing the 1 to 1.5 mm clearance air gap for the uncertainty level about mechanical interference due to possible deformation of the plastic materials. This has modified the initial length of the magnetic path (clearance + magnets + windings) from 51 to 54 mm resulting in the reduction of about 6% in the flux and induced emf; increasing the current of about 6% the machine can give the requested torque but with an increased loss of about 12% and a consequent reduction in the efficiency of about 1%.

7. EXPERIMENTAL TESTS

The motor prototype has been bench tested in "normal" environmental conditions to assess the performance against the analytical forecasts.

The tests can be subdivided as follows:

- the functional tests to verify the basic technical solutions adopted in the motor construction;
- the motor parameter estimation tests to validate the FEM analysis and parameter computation and to tune the design procedure for further optimizations;
- the thermal tests to verify the motor rated performance and the thermal-mechanical behaviour of the plastic materials and the resins used in the stator and rotor discs.

7.1 The functional tests

Beside the routine tests on winding resistance and isolation, the generator test (back-emf waveform) shows the pure sinusoidal nature of the motor, according to the 5/6 magnet pitch design. The analysis of the waveforms acquired (for example Fig. 12) has revealed a 3% content of third harmonic.

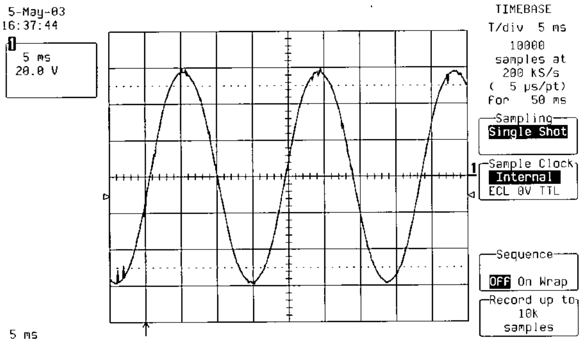

Fig. 12 Acquired phase back emf @ 400 rpm.

7.2 The parameter estimation tests

The machine has no saliency so the d and q values are almost identical and the equivalent circuit in the conventional d-q axes representation is equal for the two axes (Fig. 13).

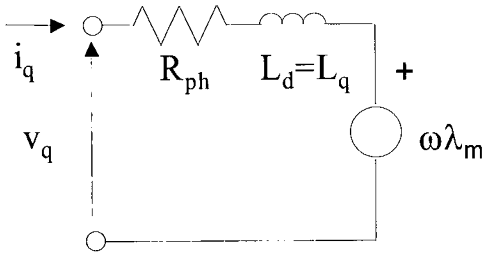

Fig. 13 q axis equivalent circuit.

Hence the parameters to be experimentally determined are:

- the constants K_V and K_T (where $K_T = \sqrt{3}K_V$) determined respectively by the no load test and the locked rotor current-torque test [8], [9];
- the d-q axes equivalent circuit parameters evaluated by performing the standstill time response test [8], [9].
- To summarize, in Table VI three values of the motor parameters are reported:
- the value computed starting from the initial design;
- the value computed considering the prototype realization, that is, taking into account the construction modification respect to the initial design;
- the value experimentally determined.

Table 4. Motor parameters

Parameter	Computed (design)	Computed (prototype)	Experimental
R_{phase} @ 20°C [Ω]	1.73	1.73	1.74
L_{phase} [mH]	3.65	3.65	3.40
K_v [Vs/rad]	2.02	1.83	1.73
K_T [Nm/A_{rms}]	3.50	3.17	3.00

The differences between the two "computed" columns are basically due to the increased airgap in the prototype respect to the initial design; the experience will give the necessary confidence in the material mechanical properties letting to bring the airgap to the original value. The last two columns are in satisfactory agreement showing the validity of the computation method.

7.3 The performance assessment

The prototype has been equipped with several temperature sensors making possible the thermal monitoring of the most critical parts such as the coils and stator plastic discs. Then the prototype has been tested in several different loaded conditions at different speeds; in particular, the rated (Table VII) torque and speed have been successfully verified.

Table 5 motor rating (@ 75°C)

Power	2,250 [W]
Torque	21.5 [Nm]
Speed	1,000 [rpm]
Frequency	133 [Hz]
Voltage	205 [V]
Current	7.5 [A]

Finally, the prototype torque density is 1Nm/kg that is comparable with torque density range of a conventional industrial machine. In the comparison, the torque density of the motors for the industrial applications must be de-rated to take into account that in industrial applications usually there are no constrains on maximum external temperature and part of the losses are exchanged through the mechanical interface. Furthermore, it must be considered that the prototype does not optimize all the parts of the mechanical structure.

8. Final Remarks and Conclusions

A dedicated brushless PM motor with unconventional plastic (quasi) ironless structure for stratospheric aircraft propeller drive has been manufactured and tested. The experimental results basically confirm the expected motor characteristics and performance predicted during the design stage. These results position the prototype (compared with conventional PM brushless motors in terms of torque density and efficiency) in the range of premium motors. Further improvements are expected by extending the use of the advanced plastic materials. The CAD analysis points out that weight reductions are possible optimizing the structural design and adopting plastic materials for the external enclosure and the shaft.

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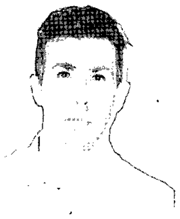

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