Magnetic mirror based on Halbach sphere for the electron-ion coincidence spectrometer

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Summer Student programme 2011,
08.09.2011
Hamburg

Abstract

This paper presents the work of Evgeny Khramov during the DESY Summer Student Programme 2011 in the group of PO4 beamline at PETRA III. The main aim of the project was modeling the pseudo-Halbach sphere using the *Mathematica*-addon *Radia* and building on its base the permanent magnet assembly suitable for use in an Electron-Ion-Coincidence Spectrometer as a highly efficient magnetic mirror.

Acknowledgements

First and foremost, I would like to thank Jens Viefhaus for the support and the opportunity to work in his group.

I would like to thank Sascha Deinert for providing an interesting topic for my work, for the discussion of the results, help with literature and working together on the BW3-beamline at DORIS.

Special thanks go to Paul Neumann for his help in the magnetic field measurements for the ring assembly.

Introduction

The Electron-Ion Coincidence spectrometer, that is being set up at BW3 DORIS beamline by the group of Jens Viefhaus, is optimized for multi-photoionization studies of gases, that can be an interesting field for atomic experimental physics. Figure 1 below presents a simple scheme of a similar setup from Egil Andersson [1].

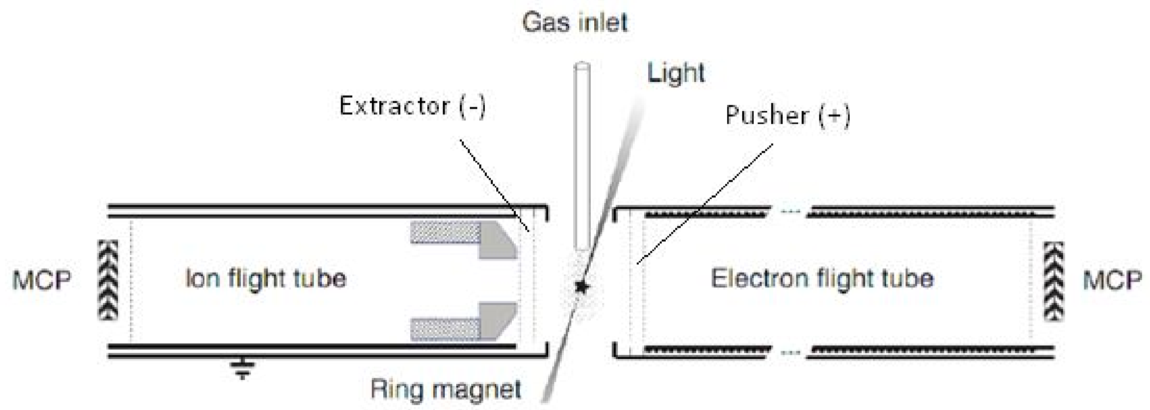


Fig. 1. The scheme of electron-ion coincidence setup . (MCP – multichannel plate)

The operation of the setup starts at the point where gas from the gas inlet is ionized by the synchrotron radiation. Then electrons are separated to the Time-of-Flight electron spectrometer (eTOF) and ions to the Time-of-Flight ion spectrometer (iTOF). Both TOF spectrometers work simultaneously, therefore electrons and ions are detected in coincidence. Electrons and ions, are separated by the electric field between the pusher electrode (+) and the extractor electrode (-). An additional magnetic field is applied, that works on the principle of magnetic bottle and guides electrons\to the MCP detector. The design of the spectrometer imposes severe restrictions on the size of the magnets used. In our case, it should not exceed 10 cm. The magnetic field generated should not only be of great value, but increase rapidly as we approach the iTOF inlet.

Another problem is demagnetization when heated, which is necessary to achieve a high vacuum. Table 1 shows the results of measurements of the field produced (in the operating point) by a prototype that was originally intended to be used at the facility, after heating it to different temperatures. The prototype is a ring assembled from NdFeB segments. The magnetization of each segment is directed towards the center of the ring. The table shows that the field produced by circular assembly, significantly decreases when heated above 90 C, which prohibits heating of the experimental setup. An improved magnet system (fig.2), which is currently used at the beamline, gives the maximum field of 0.8 T. To get the field values above 1.3 T, it is necessary to use complex magnetic assemblies, such as Halbach arrays.

t, C°	B, T
23	0,094
47,6	0,0926
57,2	0,0901
66	0,0825
77,1	0,0795
84,9	0,0745
94,2	0,0696

Table 1. NdFeB assembly demagnetization when heated

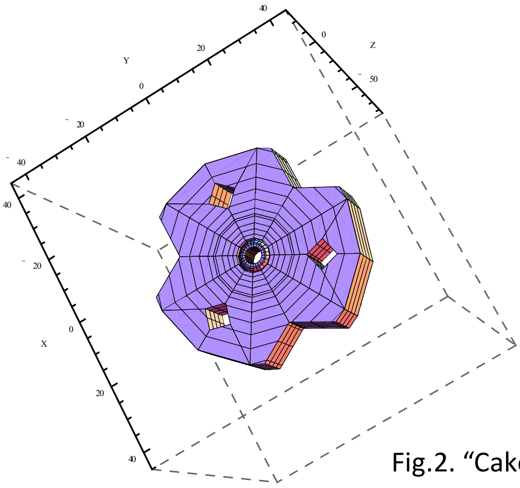


Fig.2. “Cake-shaped” magnetic assembly modeled in *Radia*

Halbach arrays

Basically, a Halbach array is a special arrangement of permanent magnets that augments the magnetic field on one side of the array while cancelling the field to near zero on the other side,

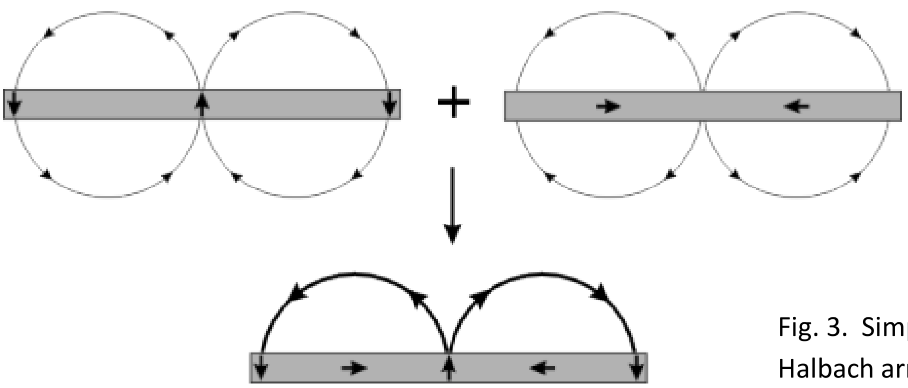


Fig. 3. Simple “linear” Halbach array

providing a *one-sided magnetic flux*. The effect was discovered by Mallinson in 1973 [2], and then in 1980 re-discovered by Klaus Halbach, who used it in the design of wigglers and undulators. The operating principle of the Halbach array can be visualised using Mallinson's original diagram (fig.3). Turning the ‘linear’ Halbach array into the ring, one can obtain the Hacbach cylinder (fig. 4), which could be extended to a hollow spherical flux source, a Halbach sphere (fig.5) [5].

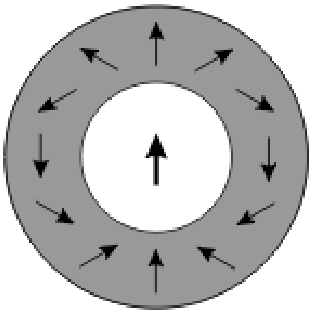


Fig. 4. Halbach cylinder [3].

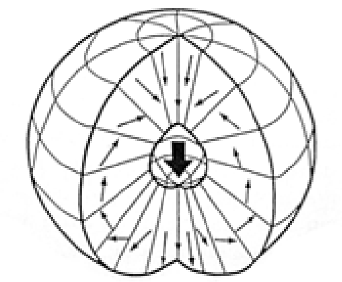


Fig. 5. Halbach sphere.

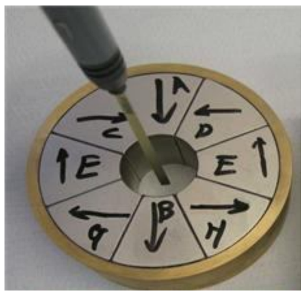
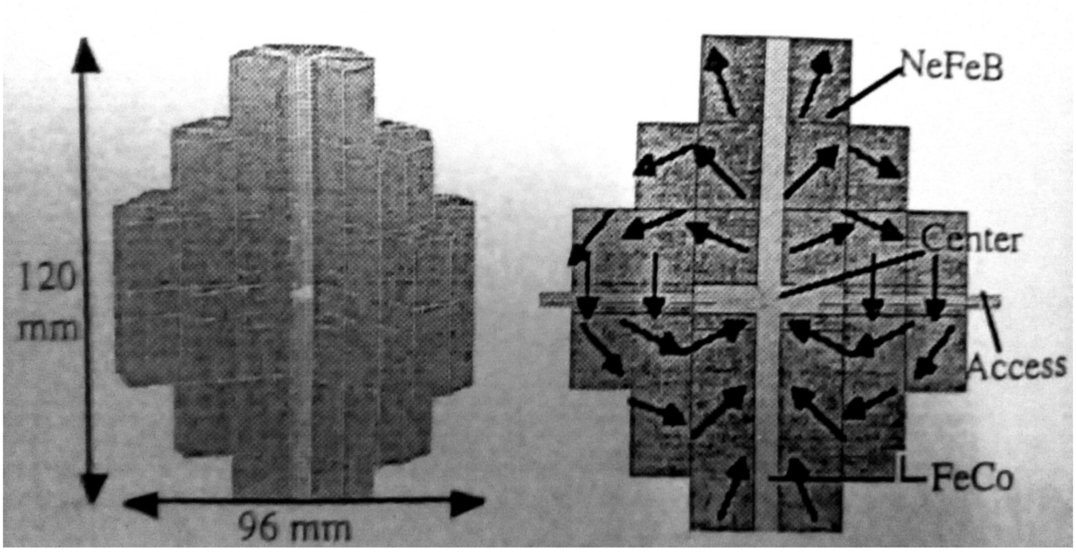


Fig. 5. Halbach cylinder assembled of 8 NdFeB permanent magnets [4].

Produce the structure shown in Figures 3 and 4, it would be technically very difficult. Real-world Halbach arrays are made from a large number of pieces, as shown on figure 6. The magnetization of each slice is uniform and the direction as the magnetization of the corresponding part of the “perfect” Halbach structure.

Higher fields are possible by optimising the spherical design to take account of the fact that it is composed of point dipoles (and not line dipoles). This results in the stretching of the sphere to an elliptical shape and having a non-uniform distribution of magnetization over the component parts of the sphere. Using this method, as well as soft pole pieces within the design, 4.5 T in a working volume of 20 mm3 was achieved by Bloch et al. in 1998 [6] and this was increased further to 5 T in 2000 [7]. Figure 7 represents Bloch’s assembly. This paper describes the results of the Bloch’s prototype simulation produced using the *Radia* software, and attempts to modify the prototype model, so that made possible its use in TOF-spectrometer.



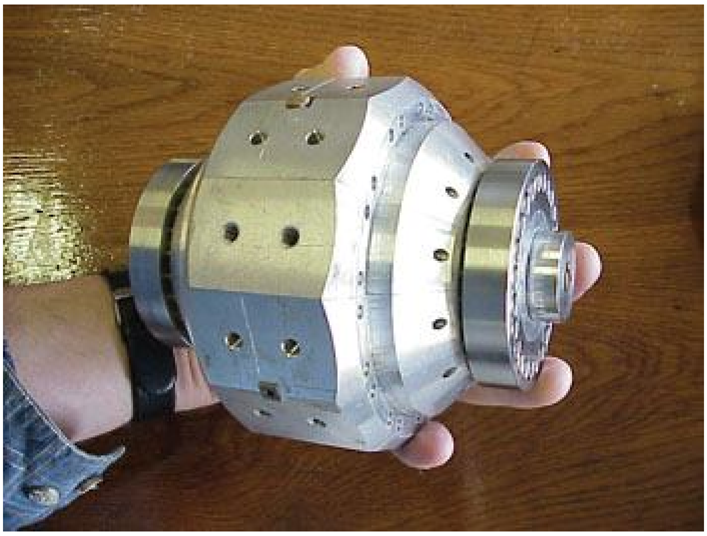


Fig. 7. Scheme and view of Pseudo-Halbach sphere assembly made by Bloch et al. in 1998

Results of modeling – Pseudo-Halbach sphere

Figure 8 shows the *Radia* simulation of the prototype described in Bloch's article [6]. In the central part of the construction one can see the tube of a soft ferromagnetic material located along the symmetry axis of the assembly (which corresponds to the X axis on the plot) to improve the generated field. As the parameters of the material for the ferromagnetic tube, the simulation uses parameters of iron-cobalt alloy Vacoflux 50. Some details, such as apertures along Y and Z axes, which are used as the access ways to introduce the samples inside the structure, have been omitted in the simulation for the sake of simplicity.

The graph in Figure 9 represents the magnitude of the field produced by the assembly at various points of its axis of symmetry (the X axis). In the center of the whole construction (It corresponds to the origin) the magnitude of the field is 4.1 Tesla, which corresponds to the results of Bloch and Cugat.

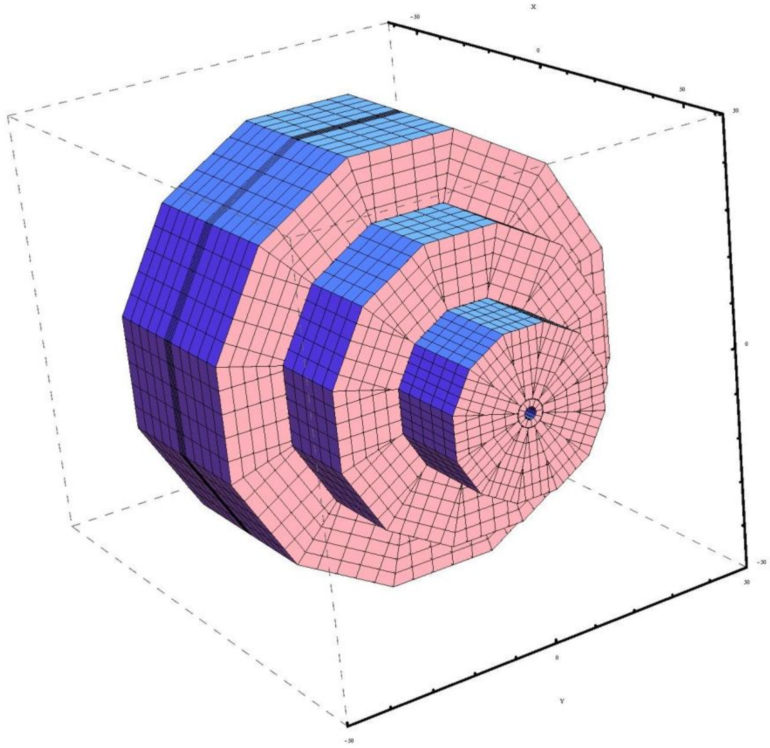


Fig. 8. The view of a Pseudo-Halbach sphere simulated in *Radia* and *Mathematica*.

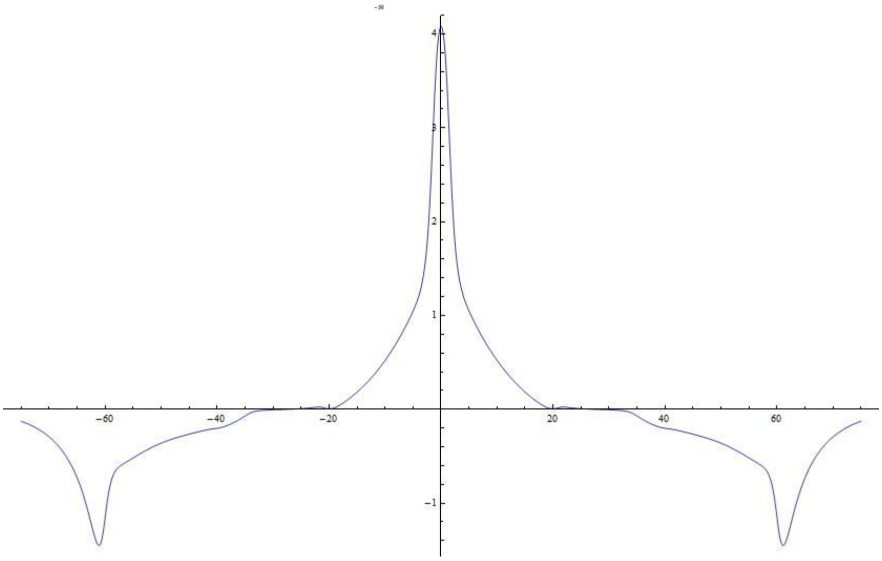


Fig. 9. The magnitude of the field produced by the assembly along the X axis.

Reducing the size of the magnetic assembly

The configuration described in Bloch's article can not be used without changes in the TOF-spectrometer to generate a magnetic field, repelling electrons. First of all, because in the interaction zone to be created not only magnetic, but also the electric field, which is created by the charged plates, that can not be introduced into the pseudo-Halbach sphere. The other reason is the design of the experimental facility that sets the limits on the size of the magnetic assembly - it should not exceed 10 cm, While the size of the Bloch's assembly is 12 cm along the X axis. Moreover, in addition to the magnets, due to the strong (up to 1000 N [6]) repulsion between them in the design of the assembly should be included the supports that hold the magnets together.

The easy way to reduce the size of the magnetic assembly and leave room for the electric field generating is to use only half of the sphere. Figures 11, 12 show results of Radia simulation for the upper half of a pseudo-Halbach sphere. Compared with the whole sphere, the field at the center point has decreased more than twice and now amounts to about 2 tesla.

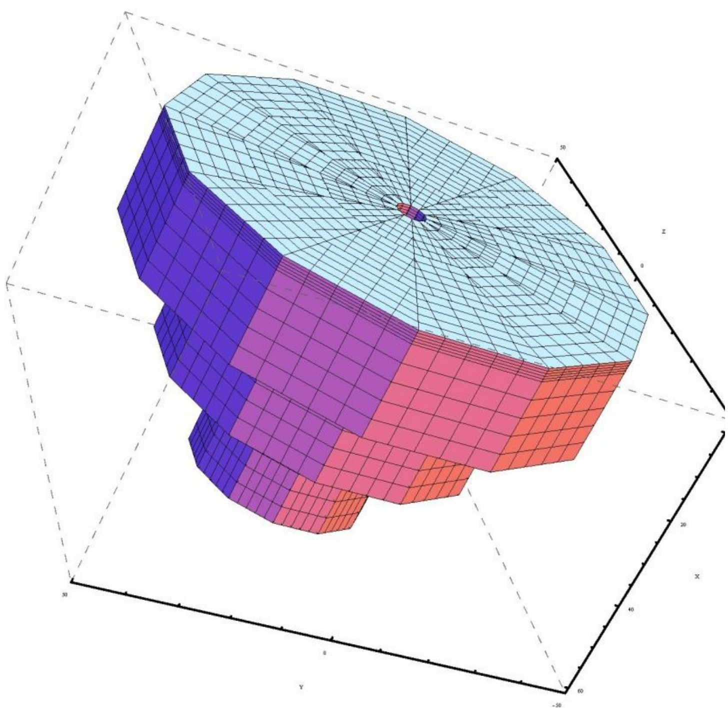


Fig. 11. The view of a half of the Pseudo-Halbach sphere simulated in *Radia* and *Mathematica*.

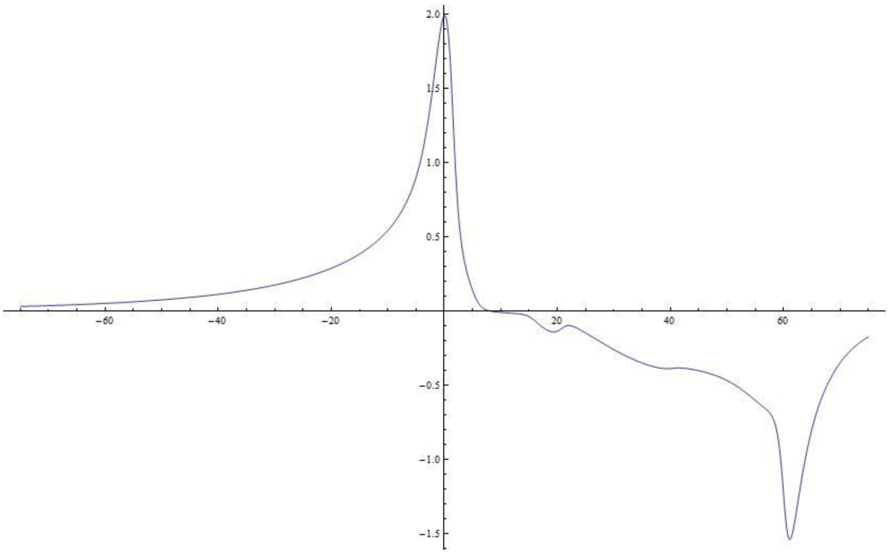


Fig. 12. The magnitude of the field produced by a half of the Pseudo-Halbach sphere along the X axis.

Figure 12 shows that the field along the axis X in the region x <0, where there would be a zone of interaction, changes relatively slowly, because of what this assembly is inefficient as a reflector of electrons. In addition, it is still relatively large. To enhance the field generated by a half of pseudo-Halbach sphere, without increasing significantly the size of the assembly, one can put it on a relatively thin basement made of ferromagnetic material. Then, since x-component of the field created by the assembly, near the base of the hemisphere is positive, the magnetization of the base will strengthen the field in the central point. To reduce the size of the assembly the magnets, which give the smallest contribution to the field at the center point, can be removed. These are the magnets that are located farthest from the center. The results of *Radia* simulation for such a modified assembly are shown in figures 13, 14.

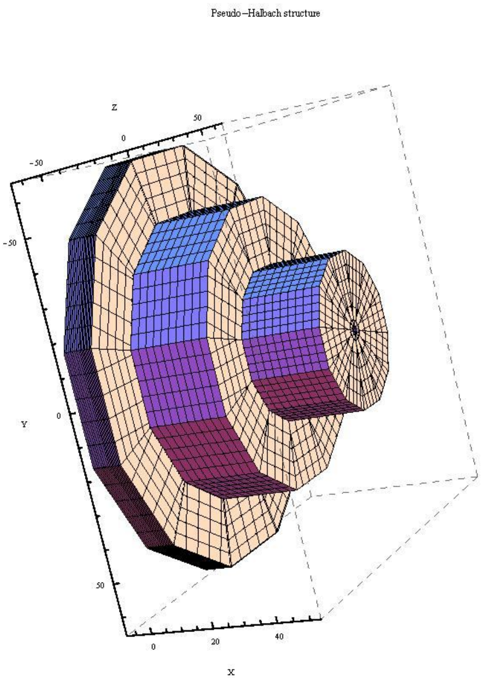


Fig. 13. The view of a 'modified' Pseudo-Halbach sphere simulated in *Radia* and *Mathematica*.

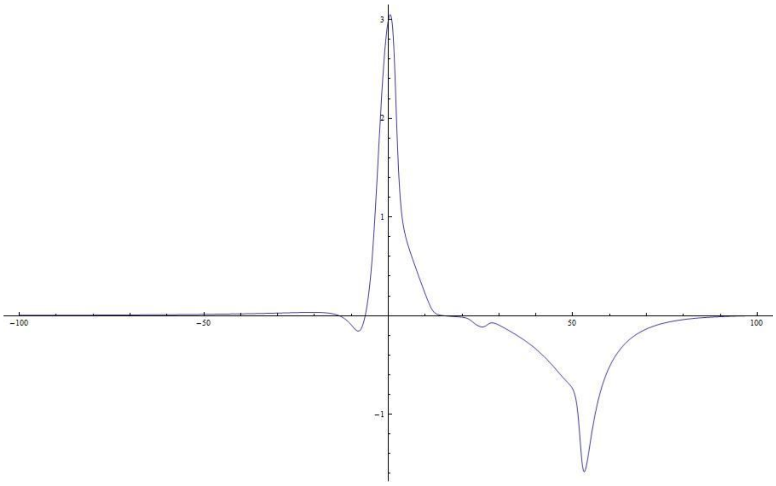


Fig. 14. The magnitude of the field produced by a ‘modified’ Pseudo-Halbach sphere along the X axis.

The field in the central point is over 3 T, and field gradient near the central point is large, so this assembly can be used in electron-ion coincidence spectrometer.

Summary

This paper shows that, starting from the Halbach array, one can build up the compact and high-field assembly of permanent magnets, which can be used as a magnetic mirror for the electron-ion coincidence spectrometer.

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