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A NEW TYPE OF PULSED AIR-CORE MULTIPOLES OF SIMPLE CONSTRUCTION

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Summary

Because of the rising cost of electric energy, pulsed magnets for beam transport systems attract increasing interest. Especially pulsed air-core systems are advantageous because of their very low weight, small volume and the possibility to install them inside the vacuum system utilizing the good insulating properties of vacuum. This paper describes some general theoretical aspects of pulsed air-core systems as well as two given examples in form of a pulsed quadrupole and a kicker magnet operating at DESY. It is well known that magnetic multipole fields of the order of n may be generated by an axial current on the surface of a circular cylinder with a current distribution of the form $I_0 \cos(n/2 \cdot \varphi)$. Since for beam optical applications only the integral field over the system length counts, it is a straightforward method to use periodic filamentary conductors on the cylindrical surface with a contour which, on averages, gives a cosine distribution. Due to the skin-effect, thin conducting sheets of the same contour are equally suitable. A rather good approximation is already attainable with comb-like conducting sheets, as will be shown in detail. It is evident that this concept leads to air-core systems of extremely simple construction.

Some principal considerations on the approximation of magnetic multipoles by filamentary conductors

For an ideal multipole of the order of n one needs a distribution of axial current of the form $I_0 \cdot \cos(n/2 \cdot \varphi)$ on the surface of a circular cylinder¹. It is evident that any geometrical arrangement of conductors with a cosinelike distribution of current on average - taken over the system length - is equally suitable for the approximation of a magnetic air-core multipole for beam optical applications, since only its integral field is relevant for its optical effect. A simple construction may be achieved with periodic filamentary conductors on the surface of a circular cylinder or on the surface of an elliptical cylinder. Such a solution may be applied to DC-operation as well as to pulsed operation. From Biot-Savart's law it may be shown² that for the periodic arrangement of fig. 1 the contribution of one conductor period to the integrated field length along the axis - as seen by a particle traversing in the z -direction at $x_p, y_p = \text{const}$ - is given by

$$L_0 \cdot \vec{H}_p = \frac{I}{2\pi} \int_{z=-\frac{L_0}{2}}^{z+\frac{L_0}{2}} \frac{\vec{k} \times \vec{r}_t(z)}{r_t^2(z)} dz \quad (1)$$

with the definition of L_0 for the period length of $\vec{k}$ for the unit vector in z -direction and of r_t for the projection of the vector r between source point Q and field point P on the x, y -plane. The important assumption of $x_p, y_p = \text{const}$ for the particle trajectory means that we are dealing with particles almost parallel to the system axis z , at least over a length equal to the period length L_0 . Obviously in practice this is always achievable by a proper choice of the period length L_0 . Returning to circular cylindrical systems, we are now able to deduce the special conductor geometry on the cylindrical surface, which gives a cosinelike distribution on the average and therefore the

ideal field distribution, when averaging over the path length of the particle.

Fig. 1: Periodic filamentary conductor (current I) with symmetry axis parallel to z -axis

According to fig. 2, where we have a periodic conductor with the current I_0 and the period length L_0 taking into account eq. (1), we have to demand

$$2 \frac{I_0}{L_0} \frac{dz(\varphi)}{r(\varphi)} = \frac{1}{2} \frac{I_0}{r(\varphi)} \cos\left(\frac{n}{2}\varphi\right) d\varphi \quad (2)$$

which gives
$$\varphi = \frac{2}{n} \arcsin \frac{2nz}{L_0} \quad (3)$$

or in general
$$R\varphi = \frac{2}{n} R \arcsin \frac{z}{L_0/4} \quad (4)$$

with φ ...azimuthal angle in cylindrical coordinates
 R ...system radius.

Fig. 2: Periodic filamentary conductor of a circular cylindrical multipole-system unwound in the $R\varphi, z$ -plane

Fig. 2 shows the function $R \cdot \varphi(z)$. Nothing will change if we take the mirror image of this shape with respect to the z -axis. When taking both, we arrive at the symmetrical structure of fig. 3, every half period of which looks like a wing. For a dipole e.g. we need two conductor systems of this shape, one extending from $-\pi/2$ to $+\pi/2$ and the other from $+\pi/2$ to $3\pi/2$ on the circular circumference. The two conductor systems of opposite current directions are not allowed to touch each other at the points $\pm\pi/2$, so that in practice the sharp tips have to be cut off a little, causing a certain error as compared to the ideal field. Another error source is introduced by the finite conductor dimensions.

pulsed mode of operation with short pulses of a few μs , one may apply comb-like conducting sheets making use of the skin-effect, which leads to a current flow on the outer contour of the sheets only, so that one has a quasi filamentary conductor. This concept allows a very simple construction of the total system and has been realized at DESY for a quadrupole (s. fig.'s 6 and 7) and for a kicker magnet with the values given in the following table. The copper comb-sheets - 1.5 mm thick - are directly installed inside the vacuum-system and the feed-throughs serve the purpose of support, radial adjustment and electrical connections. So the total system has a weight, which is hardly more than that of the vacuum tube, which is necessary anyway.

	kicker	quad.
length	400 mm	400 mm
diameter	56 mm	50 mm
inductance	0.22 μH	0.4 μH
voltage, max.	10 kV	10 kV
current, max.	5 kA	5 kA
pulse length	1.1 μs	5 μs
field/current	0.011 T/kA	0.935 T/m/kA
repet. rate		50/12 1/s

table: Data of an air-core kicker and a quadrupole realized at DESY

Fig. 6: Schematic view of pulsed quadrupole with comb-like conducting sheets
1 comb-sheet, 2 series connections

Fig. 7: Cross-sectional view of a quadrupole with comb-like sheets inside a vacuum tube on front a) and back b) side (schematic)
1 feed through, 2 conducting sheets,
3 vacuum tubes, 4 series connections

Technical aspects

It has been shown in this report that it is principally possible, to find a filamentary conductor geometry giving a cosinelike distribution of axial current on the surface of a circular or elliptical cylinder on the average. With this concept it should be possible to construct multipoles of high accuracy without ferromagnetic materials. For the practical realization of such systems we have suggested two solutions: The wire-like and the sheet-like conductor. For both techniques the influence of finite conductor dimensions on the accuracy has to be investigated in the future. In the case of a wire-like conductor a circular tube-conductor would be preferred with the advantage of an effective utilization of the conductor cross-section due to the skin-effect on the one hand and the possibility of direct watercooling on the other hand. Although the average Ohmic losses are expected to be in the order of a few hundred Watts only at pulse current amplitudes of the order of 10 kA and at duty factors around 10^{-3} as they normally occur, a watercooling is generally necessary, since the conductor-systems are to be installed inside the vacuum system. Concerning conductor heating two effects have to be taken care of: Adiabatic pulse heating and average heating. For both the max. allowable current density may be calculated as a function of pulse length and duty factor⁶. For a directly watercooled circular tube conductor of copper with an outer diameter of 4 mm as an example the allowable current amplitude is 23 kA at a pulse width of 120 μs and a rep. rate of 50/6 Hz. The adiabatic temperature rise per pulse in this case would be well below 50 K. These values may be interesting for high field dipoles. In the case of conducting sheets with wing- or comb-contours the exact current distribution over the sheet cross-section has to be further studied, especially its dependence on the pulse length. For high accuracy multipoles the assumption of quasi-filamentary currents on the sheet-contours may be too rough an approximation so that a modification of the ideal filamentary conductor geometry as derived in this paper would become necessary. However the principal idea of periodic sheet-contours is not effected by this. Obviously the sheet-solution allows a more rigid construction even when using very thin sheets, which makes it superior to the wire-solution in small-aperture-applications. At DESY prototype dipoles of the elliptical type are under construction now, which will be used for principal studies.

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