

maxon DC motor
Permanent magnet DC motor
with coreless winding

- Design, Characteristics
- Stator: Magnetic circuit
- Rotor: Winding and current flow
- Operation principle
- Commutation: Graphite brushes, precious metal brushes
- Service life, bearings

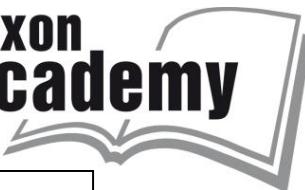
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maxon motor
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This presentation shows the design and operation principle of the maxon DC motor.

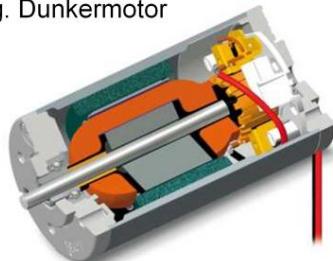
These are small DC motors with permanent magnets and winding without iron core.

- In a first part we present the differences to the conventional DC motor with iron core and the advantages of such a coreless design.
- The second part treats the magnetic circuit in the stator and some of the characteristics of the permanent magnets in use.
- In the third part we have a closer look at the coreless winding and the current flow.
- Then we investigate the interaction between current and magnetic field and the influencing parameters.
- In the fifth part we present the commutation process and the different properties of graphite and precious metal brushes.
- At the end some remarks about service life and bearings.



Part 1: DC motor designs

conventional, slotted
e.g. Dunkermotor

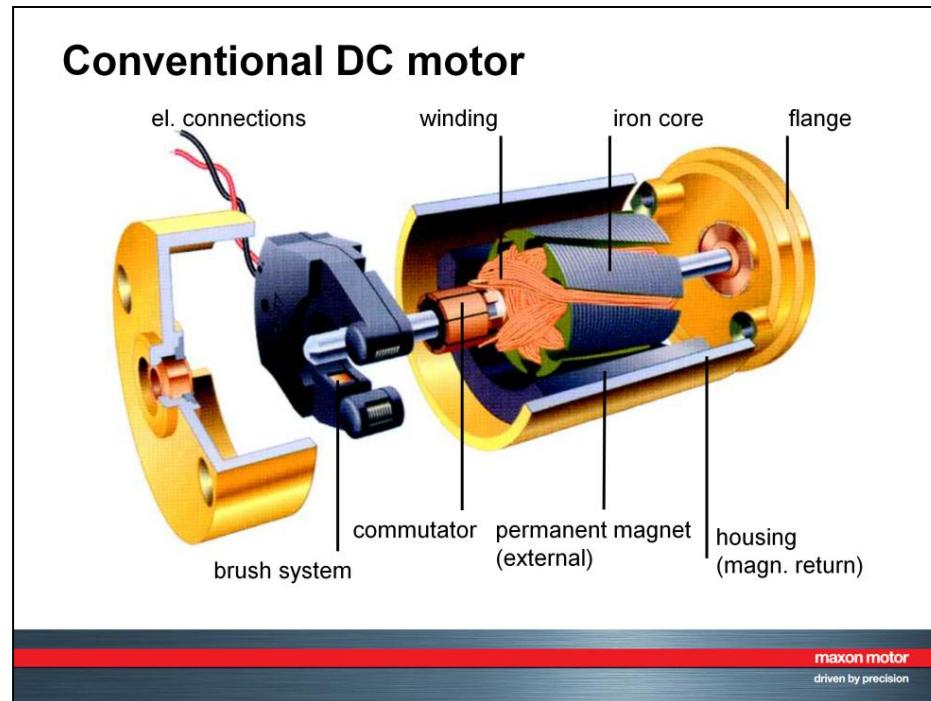


coreless
e.g. maxon

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Low power **conventional DC motors** (below approx. 1 kW) mostly use permanent magnets to produce the stator magnetic field. The winding is on the rotor side. It's wound around an slotted iron core for flow concentration and enhancement.

DC motors with ironless winding don't use the iron core. That's the system maxon uses and which is to be presented here in more detail.

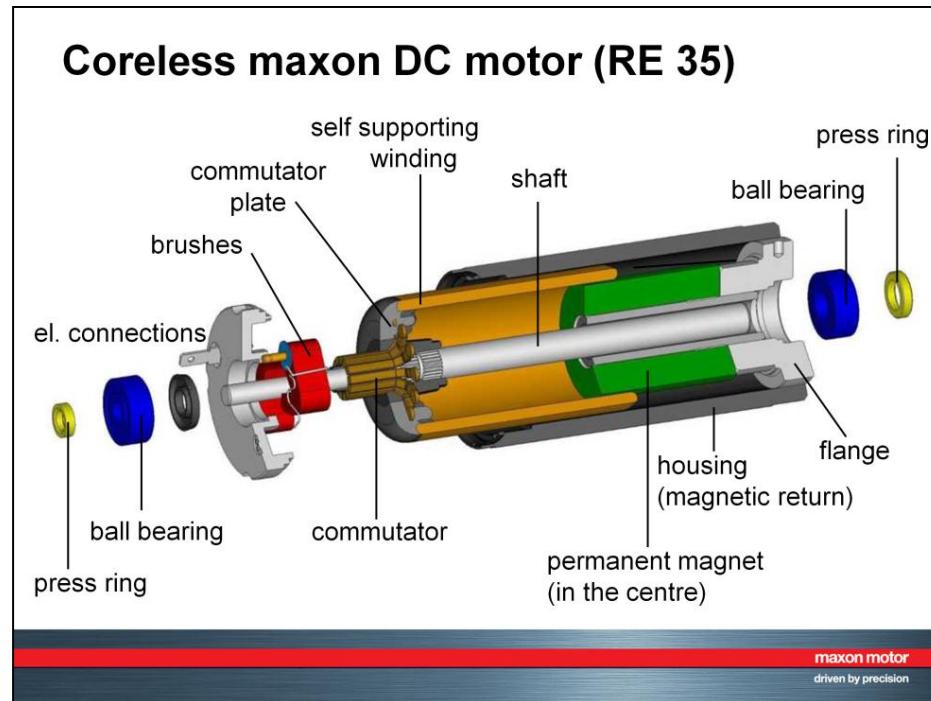


Let's have a look at a conventional DC motor. There are three main subassemblies

- The **stator** with the permanent magnet segments at the periphery, the housing that serves for guiding the magnetic flux, and the mounting flange.
- The **rotor** with winding and iron core that are mounted on the shaft. The shaft itself is supported in the stator by sleeve bearings or ball bearings. On the rotor there is also the commutator where the brushes glide on and which makes the electrical contact to the winding.
- The **brush system** with the electrical motor connections.

Additional remarks concerning the conventional motor:

- Conventional motors have a cogging torque. Cogging torque describes the torque ripple due to the interaction of the teeth of the iron core with the poles of the permanent magnet. During rotation the magnetization of the teeth must be passed from one teeth to the next. As a result the rotor wants to stop at preferential positions which makes precise position control more difficult. The cogging leads to additional vibration and noise. The iron core can be diagonally slotted for reducing the cogging torque as you can see in this picture.
- The permanent magnets are at the outside, mostly in the shape of half shells which are magnetized in opposite directions. The magnets are usually made of ferrites, rarely of plastic bonded rare earth magnets.
- The winding with iron core has a high mass reducing the dynamics of the motor. But at the same time this increases the thermal load capabilities. It takes longer for the winding to heat up and it is mechanically more stable at higher temperatures.



This picture shows a coreless maxon DC motor. We recognize the same three subassemblies as with the conventional motor.

- The **stator** consists of the permanent magnet at the centre (here shown in green), of the housing (again serving as the magnetic return) and of the mounting flange.
- The **rotor** with winding and commutator. The winding is connected to the shaft by the so called commutator plate. In this example the shaft is supported in the stator by ball bearings. The shape of the rotor reminds of a Xmas bell; that's why it is sometimes called "bell shaped" armature. The winding moves in the air gap between magnet and housing.
- The **brush system** here with graphite brushes in red and with the electrical motor connections.

The next slides show the advantages of a ironless motor design.

Advantage coreless: no cogging

- no soft magnetic teeth to interact with the permanent magnet
- smooth motor running even at low speed
- less vibrations and audible noise

- any rotor position can easily be controlled
- no nonlinearities in the control behavior

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Coreless motors have **no cogging**; there are no soft magnetic teeth. The produced torque is uniform and results in a jerk-free and smooth operation even at low speeds. At higher speeds the motor excites **less vibrations** reducing the **audible noise**.

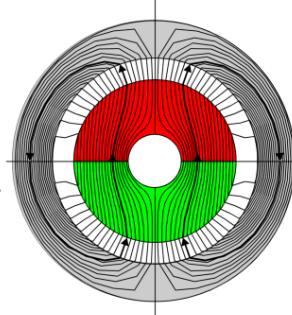
From a control point of view there are some advantages as well. The uniform torque is **simpler to control** and the motor doesn't show the tendency to stop at preferred positions.



Advantage coreless: no iron losses

- no iron core - no iron losses
- constantly impressed magnetization
- high efficiency, up to over 90%
- low no-load current, typically < 50 mA
- does not apply to EC motors

- no saturation effects in the iron core
- Even at the highest currents the produced torque is proportional to the motor current.
- stronger magnets = stronger motors



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Coreless DC motors have **no iron losses**.

In a conventional design the iron core permanently changes its magnetization. This consumes energy because the magnetic hysteresis loop must be run through at each shaft rotation. Additionally these flux variations induce Eddy currents in the iron core resulting in power losses that grow with the square of the motor speed.

By contrast, in a coreless motor the Magnetization is permanently impressed and constant. (The influence of the magnetic field of the winding can be neglected in a first approximation.) Hence there are no iron losses. As a result, the power losses are smaller, the **efficiency is higher** and the **no-load current is lower**.

In an ironless design **no saturation** at the narrow parts of the iron core (at the base of the teeth) can occur. Hence the produced torque remains **exactly proportional** to the motor current and one can use the strongest permanent magnets without being limited by the maximum magnetic flux in the iron core. Improvements in magnet technology lead to **stronger motors**.

Advantage coreless: compact design

- more efficient design of the magnetic circuit
 - (even with a larger air gap)
 - compact magnet in the centre
 - high power density
- small rotor mass inertia
 - hollow cylinder vs. plain cylinder
 - high dynamics
 - typical acceleration times: 5 - 50 ms

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The use of high performance magnetic materials gives **compact motors** with high power density.

The central magnet results in a "long" permanent magnetic part of the total magnetic circuit. This leads to a high magnetic flux density in the air gap, further enhanced by the use of the strongest magnets. Hence the produced torque increases.

Without iron core, the rotor is a hollow cylinder with a considerably **lower mass inertia**. In combination with the high torque this results in very **dynamic drives** with mechanical time constants of a few milliseconds. The strongest maxon motors have time constants even as low as 1 ms.

Advantage coreless: low inductance

- less brush fire
 - Commutation: Closing and opening of a contact over an inductive load
- longer service life
- less electromagnetic emissions
- easier to suppress interferences:
 - capacitor between connections
 - ferrite core at motor cable
- fast current reaction
 - might cause problems with pulsed supply (pulse width modulation PWM)
 - motor choke needed?

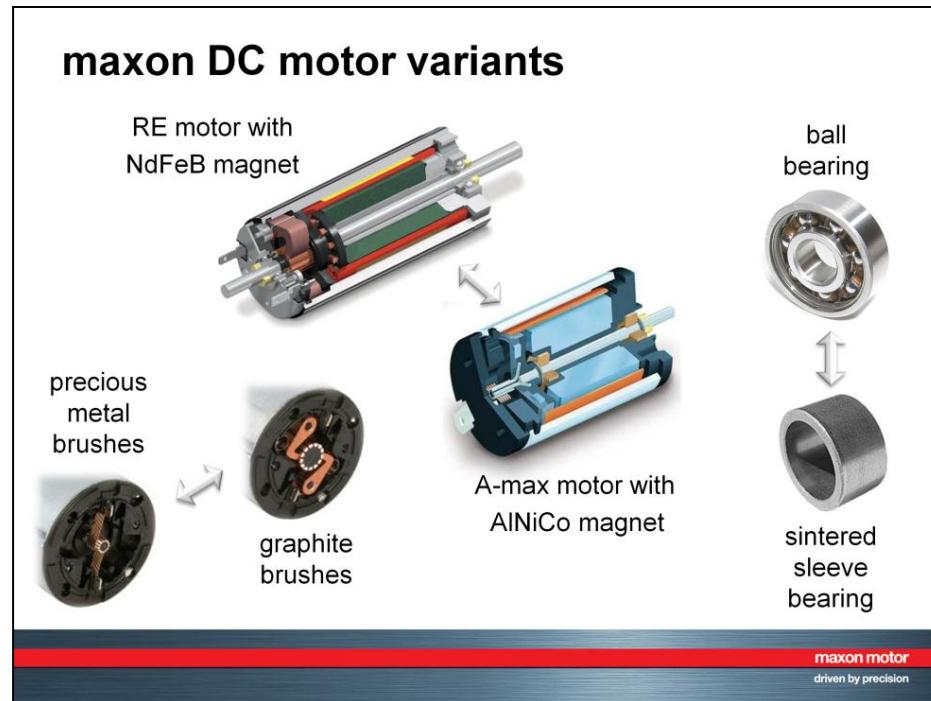
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From an electrical point of view the lacking iron core means that the **winding inductance** is much smaller. There is less magnetic energy involved in the current switching process during commutation. This reduces the brush fire - the typical discharges that occur when the contact on an inductive load is broken up.

- The commutator-brush system is less affected and has a **higher service life**.
- The reduced brush fire creates **less electromagnetic emissions**. These interferences are easier to suppress on coreless motors - if ever needed. For instance a simple capacitor between the motor connections might be all that is needed or ferrite core on the motor cable.

The low inductance also causes the motor current to react very fast. With pulsed supply (e.g. by pulse width modulation, PWM) there might be a **current ripple** that can strongly **heat up** the motor. The rapid current reaction might also affect the **stability of the current control loop**.

A **motor choke** (inductance) mounted in series to the motor can help against these problems. maxon controller which are specially designed for the low inductance maxon motors have the motor choke already included.



What are the **differences** of the different maxon motors?

Basic possibilities for variation

- different **magnetic materials**: AlNiCo, NdFeB, ferrite, ...
- **Commutation**: Graphite brushes or precious metal brushes
- **Bearings**: Sintered sleeve bearings or ball bearings

The **motor family** reflects the magnet type used: e.g. RE motors have NdFeB magnets.

Depending on operation conditions and power each DC motor type can be equipped with either bearing or commutation type.

maxon DC motor families

- RE motor range
 - power optimized
 - high performing DC motor with NdFeB magnet
 - high torques and speeds

- A-max motor range
 - attractive price-performance ratio
 - DC motor with AlNiCo magnet

- RE-max motor range
 - performance between RE and A-max



Ø 6 - 65mm



Ø 12 - 32mm



Ø 13 - 29mm

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This slide gives a summary of the **maxon DC motor family**.

- The **RE motors** are equipped with the high power Neodymium magnets. The motors are designed for high performance. These are the motors with the highest power density (combination of speed and torque) on the market. Further characteristics are: A robust design (metal flange), reliability and a comparably high service live for a brushed motor.
- The philosophy behind the **A-max motor** is different: It's about a good price-performance ratio. The motors are equipped with AlNiCo magnets with a lower power density. The flange is made of plastic and production is automated to a high degree. A-max motors are typically used in OEM appliances.
- The **RE-max motor** combines the high power of NdFeB magnets with the efficient production and design of A-max motors. The result is a motor with a performance and a price between A-max and RE motors.
- Besides these three actual motor families there are older designs, called **S A or F motors**.

maxon DC motor families comparison

permanent magnet motor range	AlNiCo A-max, S, A	NdFeB RE, RE-max
example	A-max 19 GB	RE 13 GB
speed / torque gradient	1150 min ⁻¹ /mNm	1250 min ⁻¹ /mNm
rated power	2.5 W	3 W
diameter	19 mm	13 mm
length	31.5 mm	34.5 mm
motor dimension	8.9 cm ³	4.6 cm ³
cont. torque	3.8 mNm	2.4 mNm
approximate price	≈ 50.- CHF	≈ 100.- CHF



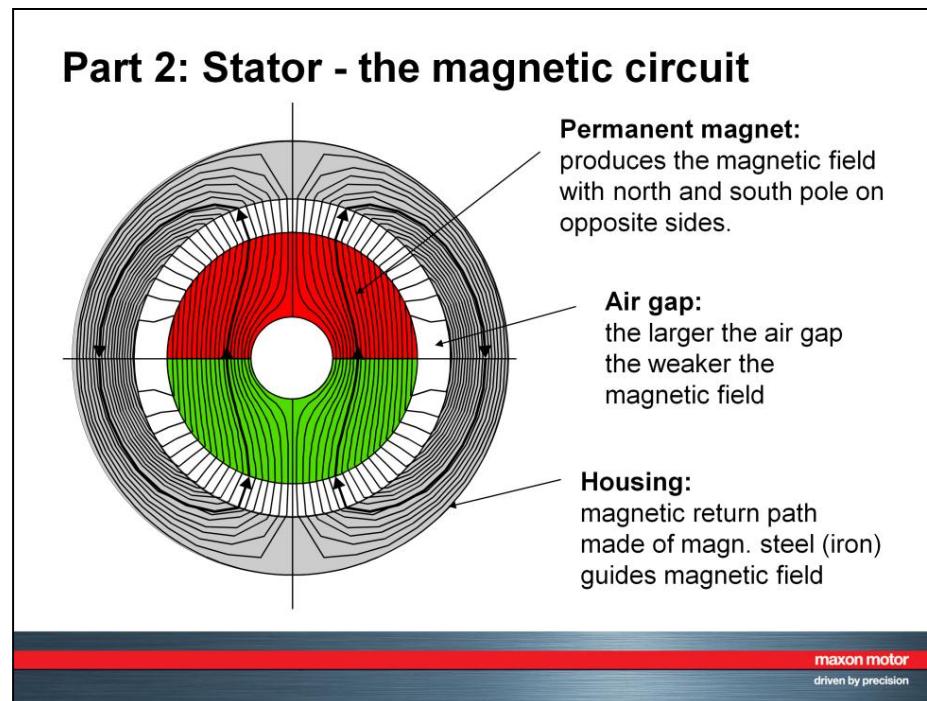
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How does the choice of the permanent magnet affect motor size?

Lets compare two motors from different families with quite similar performance (similar power rating and similar speed-torque gradient).

- **A-max-Motor.** AlNiCo magnets were the first magnets used in coreless motors. More and more they are being replaced by the stronger Neodymium magnets. The A-max philosophy is based on a cost-effective design using - among others - plastic components. Here, the performance is produced in an outer diameter of 19 mm.
- **RE-Motor.** Here the high power Neodymium magnets are used. Hence, the motor diameter is still smaller, i.e. 13 mm. However, at higher costs.

The coreless technology needs magnetic materials at higher costs and manufacturing is more complex compared to a conventional motor design. Therefore, coreless motors are usually more expensive. Coreless motors are typically used in applications with limited space available (small appliances), with weight restrictions (aerospace) and with high service life requirements (production equipment, medical).

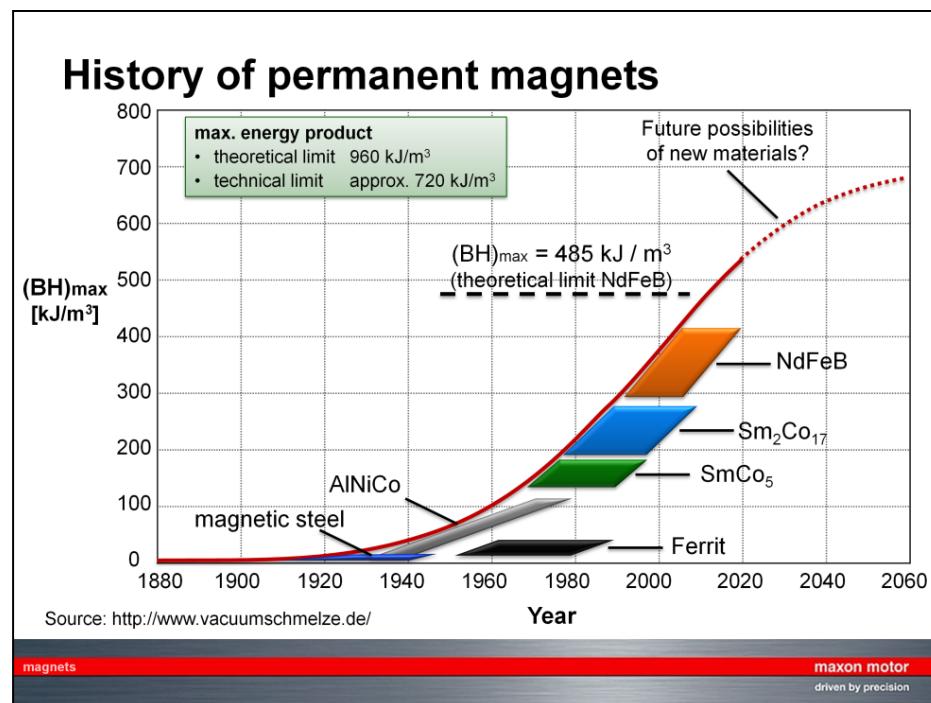


After this introduction let's now consider the magnetic circuit in the stator in more detail.

This slide shows a cross section of the stator.

- In the centre we have the **permanent magnet**. It is diametrically magnetized, the north pole being colored in red, the south pole in green. The bore in the middle serves for the motor shaft.
- The **magnetic field lines** leave the magnet at the north pole and enter the magnet at the south pole. Magnetic field lines - more exactly the magnetic induction B - are closed lines and must be guided back from the north to the south pole. That's the duty of the housing which is made of a magnetically conducting material. That's why the housing is also called **magnetic return**.
- Between the permanent magnet and the magnetic return the field lines point in radial direction in the **air gap**. The goal of this arrangement is to create an magnetic field as strong as possible in the air gap in order for the winding to produce as much force as possible. Air is a bad magnetic conductor and the larger the air gap the smaller the magnetic flux that can be built. That's why the air gap should be as narrow as possible. However in a narrow air gap there is room for only a thin walled winding. The current density is small and so is the produced force. We see that finding the right dimensions for the air gap is a classic optimization problem depending strongly on the properties of the permanent magnet.

In short: We have a configuration producing a magnetic field in the air gap which points from bottom to top in this representation.



A few words about **permanent magnets**.

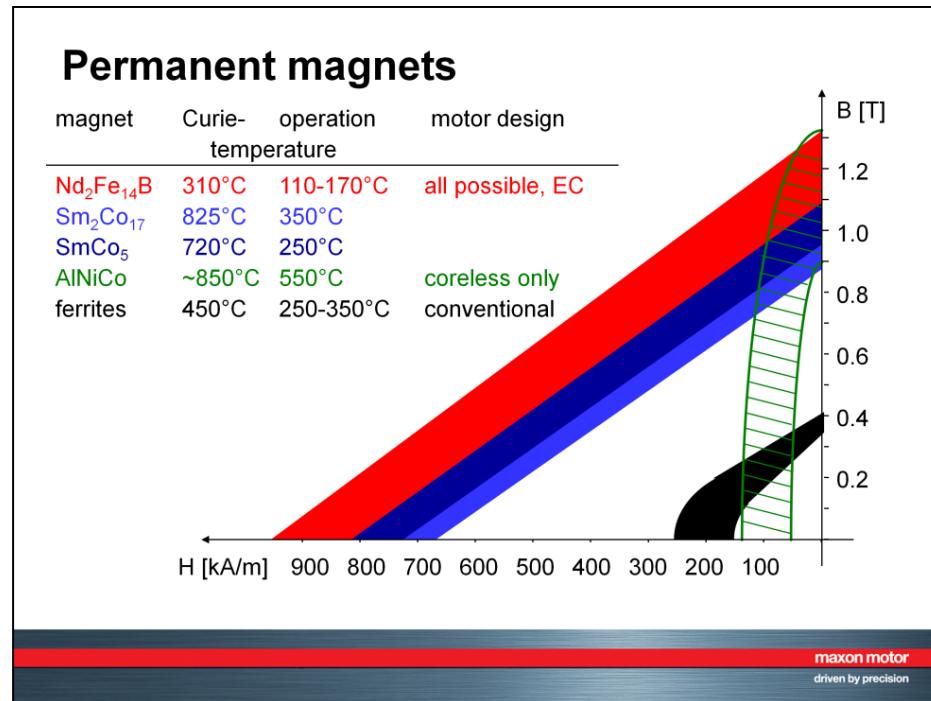
This slide shows the **development of the power density** of permanent magnets in the last century

- It all started with magnetic steels from which the AlNiCo magnets evolved in the middle of the century becoming the strongest magnet material. Improved manufacturing processes in the 60ies allowed to create an internal structure, an anisotropic axis. This further enhanced the energy product. This material together with the ferrites was at the base of the development of small permanent magnet DC motors. The higher energy density of AlNiCo compared to the ferrites was reflected in the higher power density of coreless DC motors compared to conventional DC motors
- In the 70ies the first rare earth magnets based on Samarium and cobalt appeared. They were much stronger than AlNiCo. In the 80ies the even stronger Neodymium-Iron-Boron magnets emerged on the market. Only ironless designs can make the full use of their strength resulting in the extremely high power density of coreless DC motors.

However, power density is just one parameter among others in magnetic applications.

- The magnets should be able to be easily magnetized
- In motors the magnets must support the heat without losing power or change irreversibly.
- Mechanical stability, ease of manufacturing, corrosion resistance are further important features.
- And of course the cost. In DC motors the magnet cost can amount to as much as 40%.

Newer, stronger materials that can be produced and machined reasonably don't seem to appear in the next future. The developments point rather in the direction of improving thermal and chemical stability and enhancing the remanence of existing magnets.



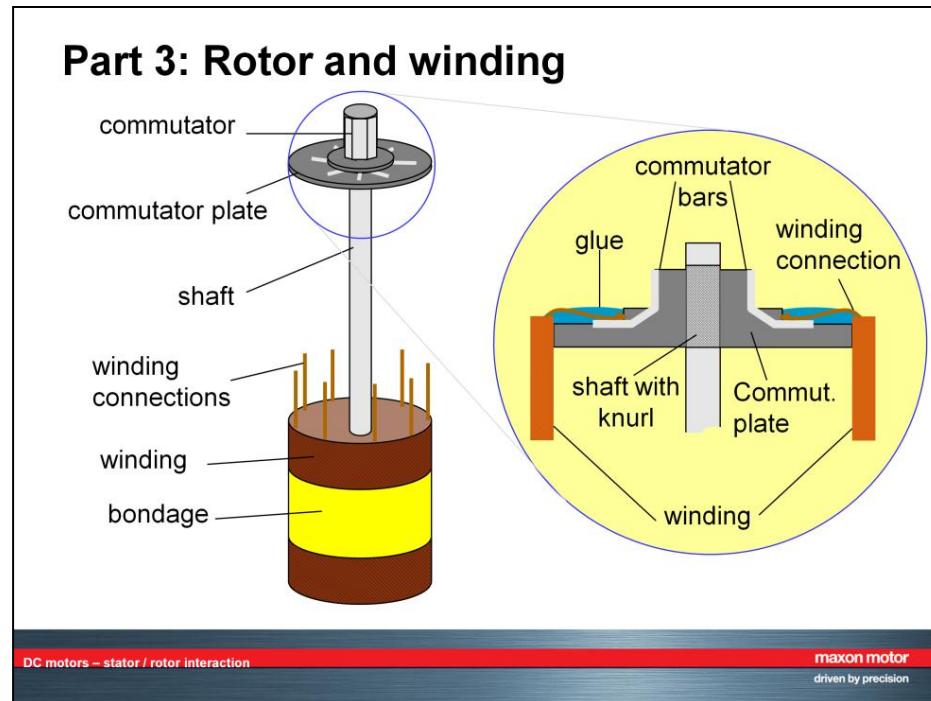
This diagram shows the areas where the typical **demagnetization curves** of different magnetic materials lie.

On the vertical axis we have the **magnetization** (or more precisely the magnetic induction B), to the left we have the external **demagnetization field H**, pointing in the opposite direction. Magnetization decreases with increasing field H.

- The magnetization at zero external field is called remanence or residual magnetism. It tells you how much a magnet can be magnetized. One can see that AlNiCo and NdFeB can have a very high remanence of more than 1.2 Tesla.
- The field H where the magnetization or magnetic induction vanishes is called coercive field. One can see that rare earth magnets have a very high coercive field which means they are difficult to demagnetize.

Increasing the air gap in a motor has a similar effect as increasing the demagnetization field. In AlNiCo motors with the very steep demagnetization curve only narrow air gaps can be made in order to have a considerable magnetic induction. Accordingly the coreless winding has a very thin wall thickness.

In RE motors the air gap can be made much larger. The winding is thicker and the motor as a whole is stronger. (These effects quite nicely show what's behind the "energy product" of permanent magnets.)



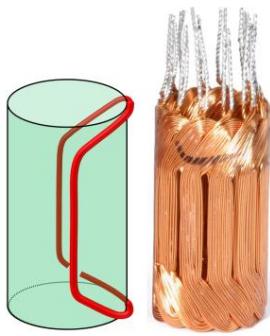
Let's now leave the stator and have a closer look at the rotor.

- In the centre there is the **shaft** made of hardened steel. The **commutator plate** is manufactured and fixed on the shaft by plastic injection molding. In the commutator plate there are the commutator bars as well.
- At the outside of the commutator plate the **self supporting winding** is fixed. The contacts of the windings are welded on the commutator bars.
- At the end the commutator plate is covered by a **glue**. This protects the contacts and welding points and gives the mechanical strength between winding and commutator plate. The torque produced in the winding has to be transferred via the commutator plate to the shaft.

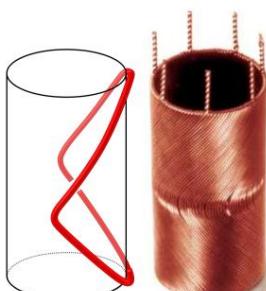
Coreless winding systems

coreless (DC) - slotless (EC)

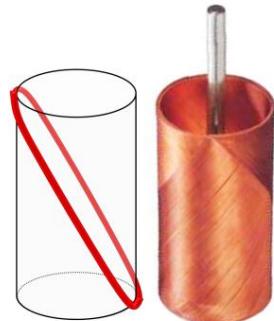
maxon
and others



maxon



Faulhaber
Portescap



Source: Portescap

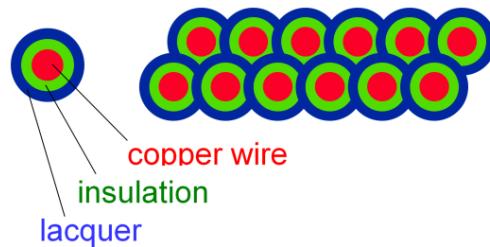
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maxon is not the only manufacturer of coreless motors with self supporting winding.

- The shape of one winding turn of the **maxon winding** is rhombic (here displayed in the middle)
- In the **Faulhaber system** (on the right) the wires run diagonally on the winding cylinder.
- For very long winding cylinders it might be favorable to have a **hexagonal wire loop** (on the left)



Winding: Enamelled wire

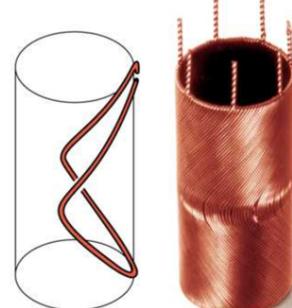


lacquer: plastic with solvent

- at higher temperatures (130-150°C):
 - lacquer of neighboring wires melts together
 - pressing forms the winding in narrow tolerances
 - out gassing of solvent: plastic hardens
 - baking of the winding

copper core:

- good electrical conductor
- insulation:
- no short-circuits



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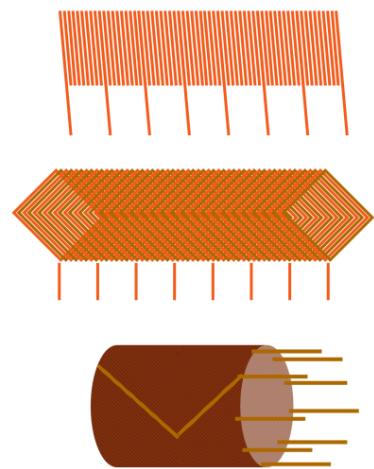
Self supporting windings without iron core are made of a so called **enameled wire**. This is an insulated copper wire with an external layer of lacquer. During the manufacturing the lacquer of neighboring wires is melted together by applying pressure and temperature.

The lacquer is a thermoplastic containing a solvent that makes it easy formable. During the high temperatures in the manufacturing process the solvent gasses out and the thermoplast becomes hard. This results in the necessary stability and stiffness of the winding.

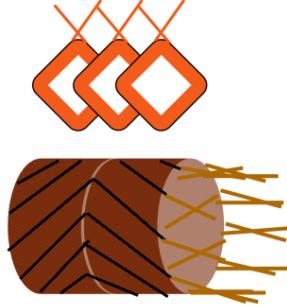
The strength and form stability of the winding are further enhanced by a **suitable bondage** (tape or glass fiber). This particularly important at high current load where the winding gets hot and the lacquer becomes softer.

maxon winding: Standard and knitted

standard maxon winding



'knitted' maxon winding



'knitted' winding for

- large motors with NdFeB magnet
- RE motors, EC motors
- thick-walled windings

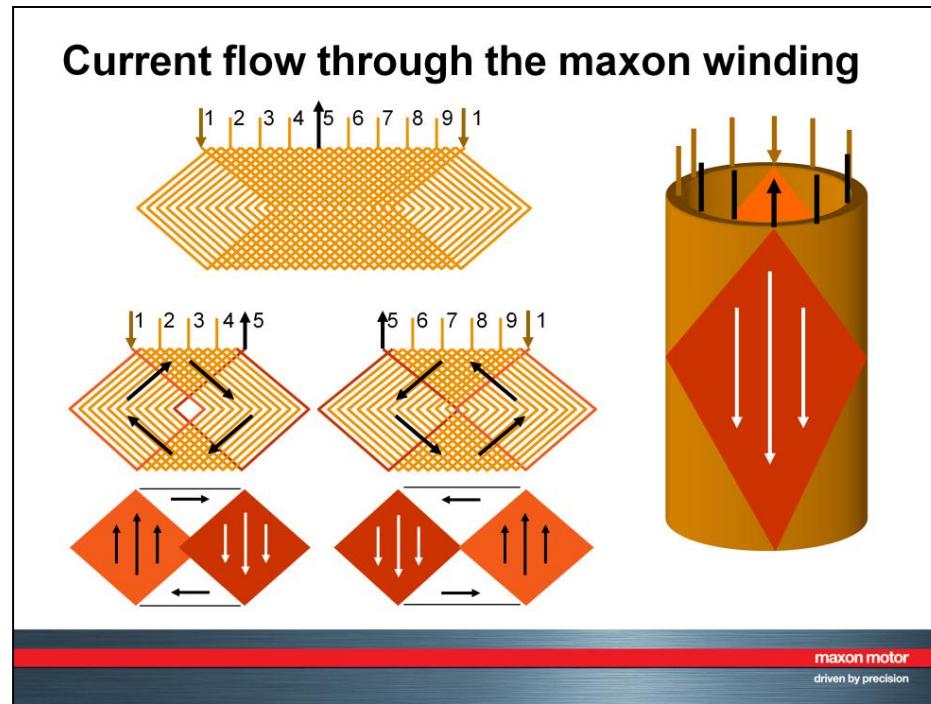
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The maxon winding exists in two basic types:

Thin-walled windings (e.g. for the narrow air gaps of A-max motors) are produced as one piece.

- The wire is wound in a flat band, and in regular intervals the connections are made.
- Then the typical rhombic shape is made and the band is rolled into a cylinder.

Thick-walled windings (e.g. for the large air gaps of RE motors) are composed of individual winding segments, or "knitted". This process is much more time consuming.



It doesn't matter if standard or knitted maxon winding: The **distribution of the current flow** is basically the same

Diagram on the right.

- The current is fed on one side by one of the brushes. Then it splits up, half of the current flows through the lift part of the winding, the other half of the current through the right part. At the opposite contact, the two currents reunite and leave the winding through the other brush.

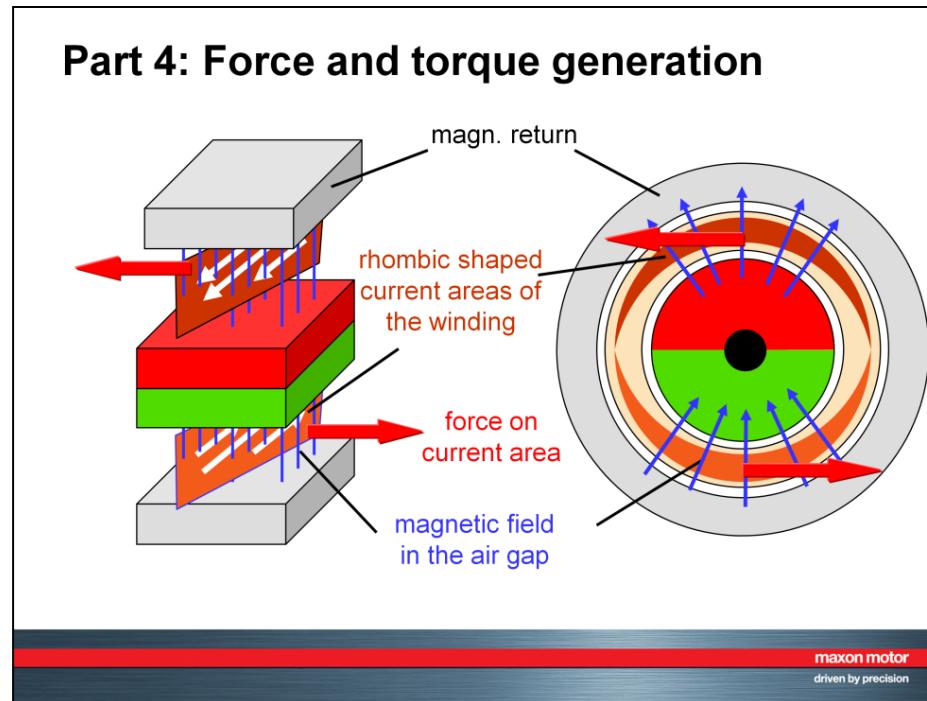
The diagrams on the left show the deeper analysis of the current distribution.

- Let's consider the winding as an open band again where the current enters the winding at the first and last connection and leaves it in the middle.
- Looking separately at the two parts of the winding we can see that the current flows in a circular way in opposite directions in the two halves. A more detailed analysis of the average current gives two triangular shaped areas on top and at the bottom where the average current flows to the left or right. (On the winding cylinder these currents point in a tangential direction and don't add to the motor torque.)
- Besides there are two rhombic shaped areas on the left and right with a current flow which is essentially directed to the top or to the bottom. In the motor these current flow in axial direction. Adding the two halves of the winding we even get an exactly axial average current.

In summary we get **two rhombic shaped current areas** on opposite sides of the winding cylinder. The current is in axial and opposite direction. The angle of the rhombuses lies at the winding connection that carry the current.

By the way: If one analyses the current flow in a Faulhaber winding one obtains exactly the same rhombic shaped current areas. From a physical point of view the two winding systems are equivalent.

Part 4: Force and torque generation



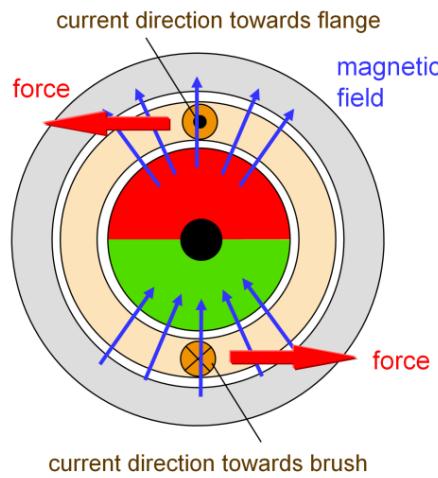
So we have now all ingredients to understand how the torque is generated. All we have is to remember the **Lorentz force** from physics classes. It describes that a current conductor in an external magnetic field experiences a force. The force is perpendicular to the current and the magnetic induction field and the "right hand rule" applies.

- In our arrangement with the magnetic induction pointing from bottom to top and the current pointing backwards or to the front this results in forces to the left or right.
- In the motor these forces add to a torque in one and the same direction.

In summary the torque is generated by the interaction of the electrical current and the field of the permanent magnet.

(An alternative way of looking at the situation: The current in the winding can be considered as a circular current, generating a magnetic field similar to the one of a solenoid. The field of the winding is perpendicular to the one of the permanent magnet. The torque comes from the fact, that the two fields want to align.)

Torque and current: k_M


forces:

force on current conducting wire in magnetic field

torque:

sum of all the forces at a distance to the rotation axis

influencing parameter:

geometry
flux density
number of winding turns

} design

=> k_M = torque constant

$$M = k_M \cdot I$$

I = current

} application

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Let's shortly review which **parameter** have an influence on the generated torque.

- The torque is the sum of all forces at a distance to the rotation axis.
- The total force is proportional ...
 - to the strength of the **magnetic induction** B in the air gap
 - to the length of the winding and to the **geometric** shape of the current
 - to the **current** through the wire
 - to the number of wires, i.e. to the **number of winding turns**
- In order to generate the maximum torque the rhombic current areas have to be close to the poles of the permanent magnet.

If you buy a motor the geometry, the magnetic induction and the number of winding turns is fixed. The user only can change the current. From the user point of view we have: The generated torque is proportional to the current. The proportionality constant sums up all the design parameters. It's called **torque constant k_M** .

This relation between current and torque describes one part of the power conversion in the motor. It signifies that **current and torque are equivalent**.

Speed and voltage: speed constant

- rotating winding in the air gap
 - in an inhomogeneous magnetic field
 - induced voltage U_{ind} (EMF) depends on
 - geometry
 - magnetic flux density
 - number of winding turns
 - speed n
- $n = k_n \cdot U_{\text{ind}}$
- }
design
}
application
- speed constant k_n
 - inversely proportional to k_M
 - inversely proportional to generator constant (V/1000 rpm)

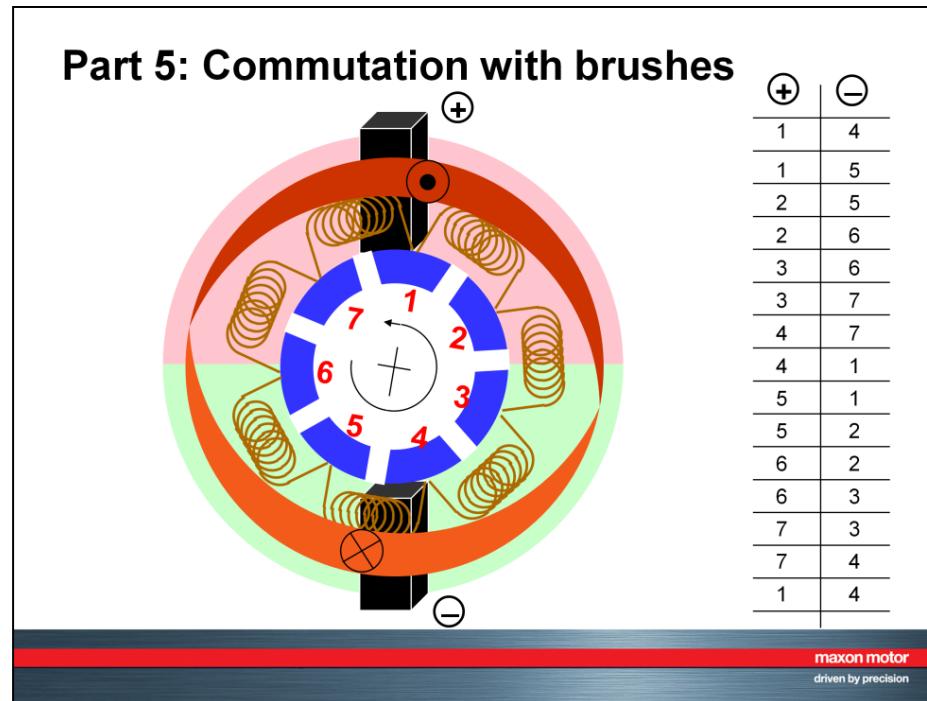
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For the sake of completeness we would like to present a second motor constant. The **speed constant** describes the relation between speed and voltage.

Physical background is the **law of induction** expressing that a magnetic flux variation through a conductor loop induces a voltage proportional to this flux variation. In the motor the winding moves through the air gap. Hence the magnetic flux changes the direction twice per motor turn (the flux varies basically in a sinusoidal manner). The total flux variation depends on the number and geometric shape of the winding turns and the amplitude of the flux. All this is given by the motor design and constant.

Hence, at the end we have: the faster the motor turns the larger the flux variation per time and the higher the induced voltage. The **speed constant k_n** describes this proportionality between speed and induced voltage.

A deeper analysis shows that the speed constant is the reciprocal value of the torque constant, but expressed in different units.



We know now how the torque is generated and the next step is to see how a continuous motion is achieved. For this we need the **commutation system**.

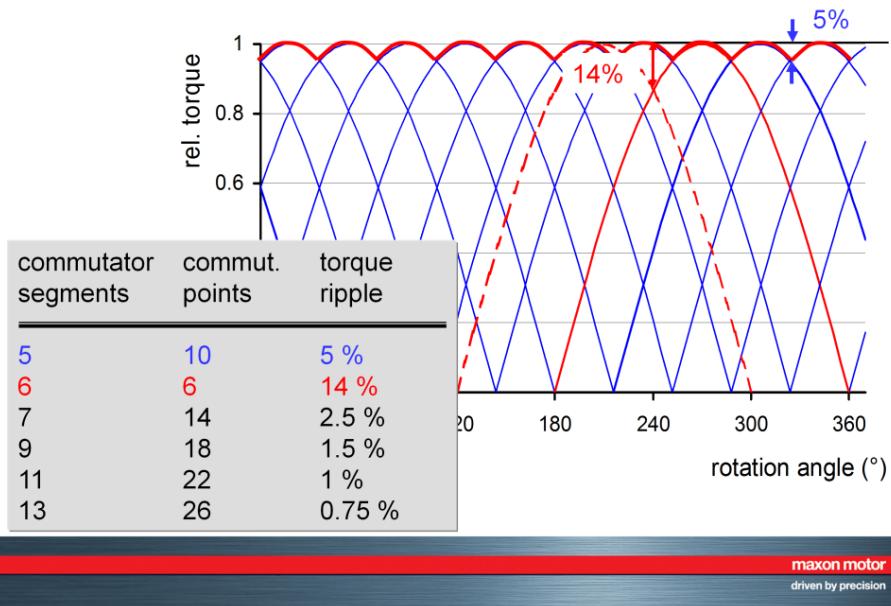
The **generated torque** causes the rotor to turn and, hence, the current rhombuses move away from the magnetic poles. The torque decreases, after a quarter turn it even vanishes and points then in the opposite direction.

Fortunately the winding has many connections, all connected to the commutator. Upon rotation the brushes automatically contact a new commutator bar and the current rhombus jumps back one winding segment and is relocated at the pole of the permanent magnet where the torque is highest. With a high number of commutator and winding segments an almost constant torque can be achieved.

maxon motors have an **odd number of commutator bars**; the commutation takes place at one brush at a time and the current flow must be switched in one winding segment only. A relative high and odd number of commutator bars has two advantages

- on one hand only a small amount of energy must be switched during commutation reducing the brush fire at the commutator. This is good for service life and the motor shows less electromagnetic interferences (EMI).
- on another hand the torque ripple due to the finite commutation angle is small, what you can see on the next slide.

DC commutation: torque ripple

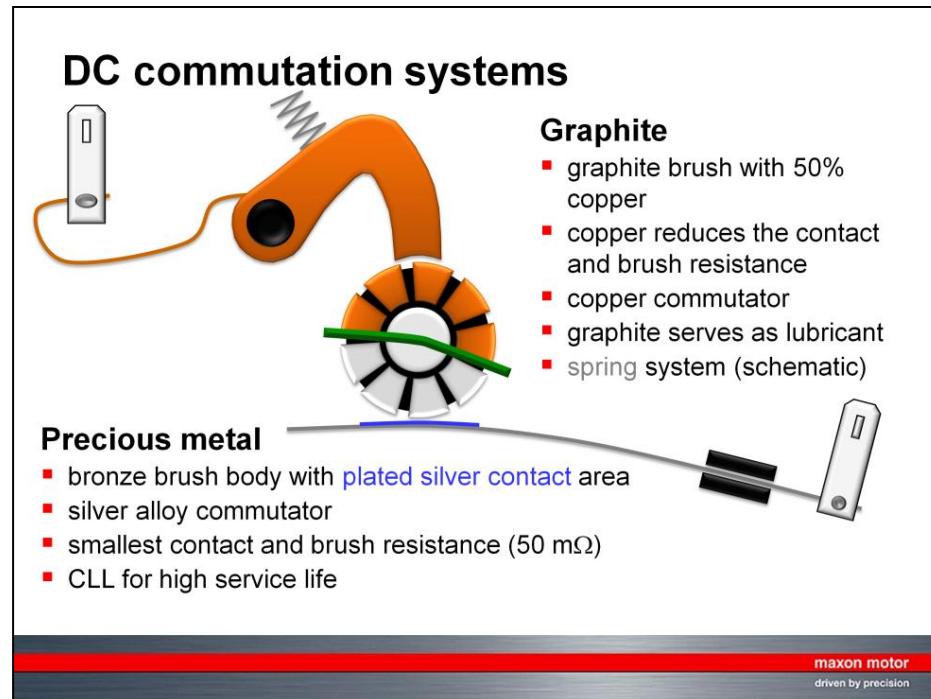


Theoretically the **torque ripple** can be calculated from the number of commutator segments and commutation points.

In a good approximation the torque for one contact situation varies in a sinusoidal manner. The more commutation points a motor has, the higher the number of sinuses that must be placed on one motor turn (for each contact pair one sinus), and the less the torque has time to decrease.

Particularly advantageous is an odd number of commutator segments because this doubles the commutation points. Hence 5 commutator segments are much better than 6.

Increasing the number of commutation segments very much however, does not give a technical advantage but increases production costs. Furthermore, the winding tolerances causes torque variations of usually more than 1%.



On small DC motors one finds two types of brush systems which are presented here for comparison.
(In one motor there is only one type! Just to make shore that this diagram is not misunderstood.)

Graphite brushes:

- Graphite brushes are often made as **lever brushes**, i.e. the rotate around an axis and are pressed against the commutator by a **spring**. There is a lot of labor involved in the production of this system with brush, bearing, spring and **strand**.
- The brush of small DC motors is made of **graphite by approx. 50%** only. The rest is copper to enhance the conductance of the brush. Otherwise a large portion of the applied voltage would be lost over the brushes.
- The commutator is made of a **copper** alloy. The commutator surface is turned on the lathe to ascertain roundness and to produce a certain roughness. This surface roughness is important for the building of the **patina**, the brownish layer made from copper oxide, water, graphite,
- Graphite brushes on copper commutator is a **well-proven gliding contact** used in many areas and in many motors. It is particularly well suited for **high current densities** because this allows to penetrate the oxide layer at the commutator surface more easily. In these cases the contact resistance is small. Graphite brushes are not very sensitive to brush fire because there should be a discharge between brush and commutator anyway.

Precious metal brushes

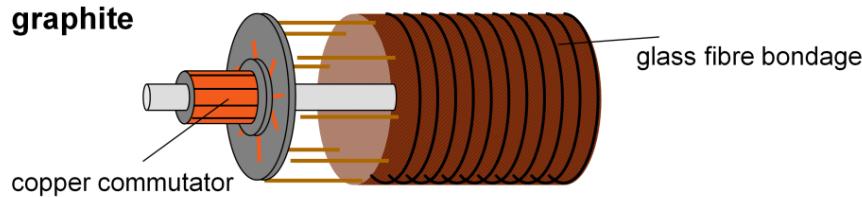
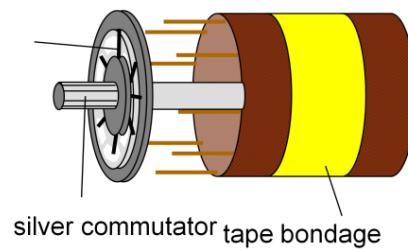
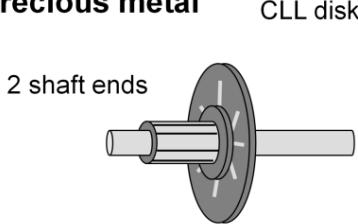
- Precious metal brushes are better suited for **small currents** and voltages. The gliding contact is directly between metal and metal and exhibits an extremely small contact resistance. Precious metals (mostly silver, rarely gold) is used to prevent oxidation.
- The brush body is made of a **spring bronze** with a **plated silver contact area**. The brush serves as a spring itself simplifying the design and reducing costs.
- The commutator is made of a **silver alloy**. The surface is finished by grinding and polishing.
- Precious metal brushes are not suited for high currents and voltages. Brush fire reduces the service life dramatically. (The reason for this is in the low melting temperature of the silver alloys and the tiny dimensions and layer thickness). Brush fire is suppressed by capacitors which are contained in the **CLL disk** (see later). To enhance service life even more, the precious metal

maxon DC motor

Permanent magnet DC motor with coreless winding
commutation is lubricated.



DC commutation: rotors

graphite**precious metal**

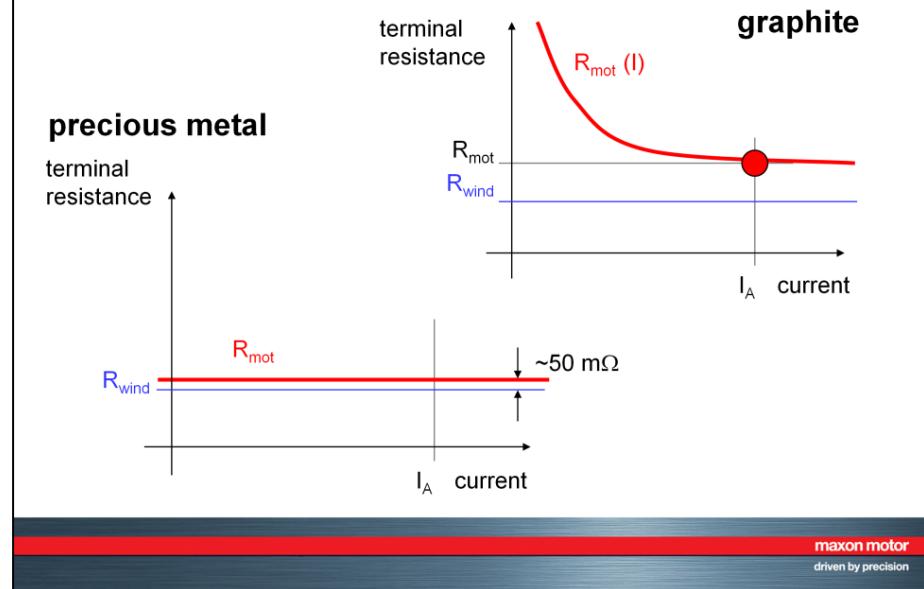
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The type of commutation also has an influence on rotor design

Copper commutators for graphite brushes have a relative large diameter. It is no problem to feed the shaft through the commutator. Motors with one or two shaft ends exhibit the same commutator diameter and hence identical maximum permissible speeds. (The maximum speed depends on the maximum relative speed between brush and commutator surface). Graphite commutation is used for high current application; the winding could become quite warm and, hence, is usually stabilized with a **glass fibre bondage**.

With **precious metal commutation** the permissible currents are smaller, the winding heats up less and a simple **tape bondage** is sufficient. In order to increase the service life the **commutator diameter is made as small as possible**, sometimes even without having the shaft entering it. On motors with two shaft end the commutator diameter must be made larger und the maximum speed is lower.

DC commutation: terminal resistance



Here some illustration about the **terminal resistance** of both commutation systems.

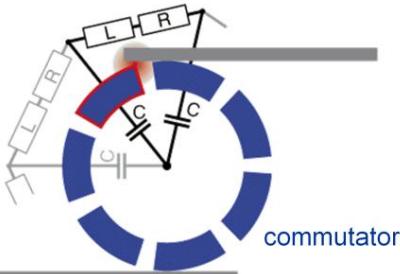
With **precious metal brushes** the terminal resistance reflects basically the winding, the contribution of the brush system can be neglected.

On **graphite brushes** the **resistance depends on the current**. Graphit is a better conductor at high currents, the same is true for the contact to the commutator. At small currents the terminal motor resistance increases strongly (aprox. with the fourth power of the current). Therefore, don't measure the terminal resistance with a multimeter (they work a very low currents). In addition the measured results may vary a lot depending on the state of the patina. Better measure the motor current in stalled condition at fixed voltage and calculate the resistance.

Precious metal commutation: CLL

Problem

- Brush fire => Reduced life



voltage
between commutator bars

200 V

10 V

time

without CLL:

- energy is released rapidly
- high voltages, sparks

with CLL:

- energy is released slowly
- damped oscillation
- small voltages

Solution

- capacitors and resistors between neighbouring commutator segments
- energy is deviated into capacitor: no arcs produced

DC motors – commutation

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As we've heard already **precious metal commutation** is very sensitive to **brush fire**. These sparks are produced during commutation when the contact between brush and commutator bar is opened. The winding represents an inductive load and the current wants to continue to flow. Brush fire is produced as well when the brush starts to vibrate and loses contact at higher speeds.

A solution for this problem is the **capacitive spark quenching**. A capacitor is mounted in parallel to the contact to open taking up the excess energy. Later this switching energy can be dissipated in the resistance.

That's in short the **CLL concept** which is realized as a disk mounted on the commutator plate and electrically contacted to the winding connections.

The **schematic** diagram at the right shows the voltages that occur at the commutator. It's based on simulations.

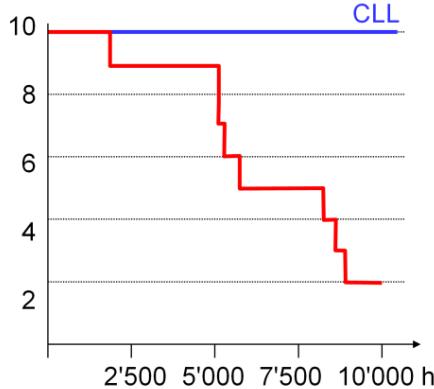
The brush short-circuits two adjacent commutator bars. Very often the current cannot fully vanish during this phase and when the contact is opened a **high voltage pulse** is generated which might be as high as several 100 V (red curve) leading to a discharge.

With the **CLL disk** the energy is deviated into the capacitor and then slowly dissipated in a damped oscillation (blue curve). The voltages that can occur are below 12 V (in the ideal case) where no discharge can occur.

Service life and CLL (examples)

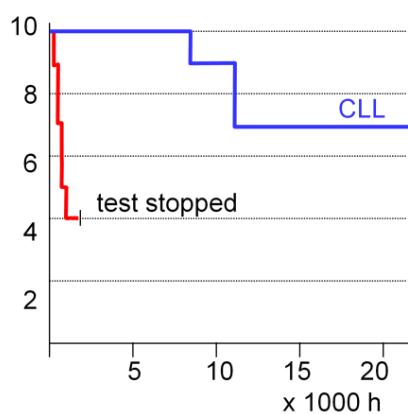
Motor 1

$I = 50 \text{ mA}$ $n = 13'000 \text{ rpm}$
 $U = 24 \text{ V}$



Motor 2

$I = 250 \text{ mA}$ $n = 1'500 \text{ rpm}$
 $U = 10 \text{ V}$



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CLL stands for "**C**apacitor **L**ong **L**ife".

That motor life is longer indeed can be seen from these **comparative life testing** results.

- The red curve refers to the number of surviving motors without CLL.
- Blue is the number of motors with CLL

On the left there is the case of a **low current load**:

- Many motors without CLL fail around 5000 hours of service. One even much earlier.
- With CLL all the 10 motors still worked after 10'000 hours.

On the right there is the case of a **higher current load**:

- First thing we see is that motor current is an important parameter influencing motor life.
- without CLL the service life was very short, less than about 1000 hours.
- with CLL it took approx. 8000 hours for the first motor to fail.

DC commutation: Characteristics

Graphite

- well suited for high currents and peak currents
- well suited for start-stop and reversing operation
- larger motors (>approx. 10 W)
- higher friction, higher no-load current
- not suited for small currents
- higher audible noise
- higher electromagnetic emissions
- higher costs

Precious metal

- well suited for smallest currents and voltages
- well suited for continuous operation
- smaller motors
- very low friction
- low audible noise
- low electromagnetic interference
- cost effective
- not suited for high current and peak currents
- not suited for start-stop operation

maxon motor
driven by precision

Let's summarize the **properties of the two commutation systems**.

Graphite commutation better suits high currents and peak currents that occur during start-stop operation. Larger Motors usually have higher currents; that's why motors with a power higher than about 10 W are equipped with graphite brushes only.

Precious metal brushes can be found on the smallest motors. They are well suited for smallest currents and voltages. They show a very small friction, generate almost no noise and - grace to the CLL - almost no electromagnetic interference.

The choice between graphite and precious metal brushes can only be made in the motor diameter range from 13 to 26 mm. Larger motors only have graphite brushes, smaller motors only precious metal brushes.

Part 6: Service life, bearings

service life

- no general statement possible
- average conditions: 1'000 - 3'000 hours
- under extreme conditions: less than 100 hours
- under favorable conditions: more than 20'000 hours

use graphite brushes and ball bearing for extreme requirements

influencing factors

- electrical load:
higher currents = higher electro erosion (brush fire)
- speed:
higher speed = higher mechanical wear
- operation mode:
continuous operation
start-stop operation
reverse operation = reduced service life
- temperature
- humidity of the air
- load on the shaft (bearing)

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Remarks about the **service life** of the maxon DC motor

In most cases it's the **brush system** that limits motor life. In rare cases it's the bearings.

Each application is different and service life can vary a lot. That's why **no general statement** can be made or even guaranteed.

- Experience shows however, that for **average conditions several 1000 hours** can be reached..
- under favorable conditions (e.g. continuous operation at low load) more than 20'000 hours or more have been reached.
- Extreme conditions such as high vibration, extreme start-stop and reverse operation can limit motor service life to less than 100 hours.

The most important point is to find out what really the needed life is for the given application, expressed in hours or number of working cycles. An interesting remark: With graphite brushes several million working cycles could be reached in several applications.

Ball and sleeve bearings: characteristics

Ball bearing

- well suited for high radial and axial loads
- well suited for all operating modes, for start-stop and reversing operation
- on larger motors
- more audible noise if not preloaded
- when preloaded higher friction
- more expensive

Sintered sleeve bearings

- suited for low radial and axial loads
- suited for continuous operation at higher speeds
- smaller motors
- low friction and noise
- cost effective
- not suited for start-stop operation

maxon motor
driven by precision

At the end some remarks about the **bearings**

Often one can select not only the commutation type but bearing type as well.

As a general rule for higher loads and requirements **ball bearings** are better.

Often **sintered sleeve bearings** can be used in the same applications as **precious metal brushes**.

The same holds for the combination of **ball bearings** and **graphite brushes**.