Ignition coils

Within the inductive ignition system, the ignition coil is the component responsible for converting the low battery voltage into the high voltage required to generate flashover at the spark plug. The ignition coil operates on the basis of electromagnetic induction: The energy stored in the magnetic field of the primary winding is transmitted by magnetic induction to the secondary side of the coil.

Function

The high voltage and ignition energy required to ignite the air/fuel mixture must be generated and stored prior to flashover. The coil acts as a dual-function device by serving as both transformer and energy accumulator. It stores the magnetic energy built up in the magnetic field generated by the primary current and then releases this energy when the primary current is deactivated at the moment of ignition.

The coil must be precisely matched to the other components in the ignition system (ignition driver stage, spark plugs). Essential parameters are:

- The spark energy W_{sp} available to the spark plug
- The spark current I_{sp} applied to the spark plug at the flashover point
- The duration of the spark at the spark plug t_{sp}, and
- An ignition voltage U_{ig} adequate for all operating conditions

Important considerations in designing the ignition system include the interactions of individual system parameters with the ignition driver stage, the ignition coil and the spark plug, as well as the specific demands associated with the engine's design concept.

1 Main Bosch ignition-coil types

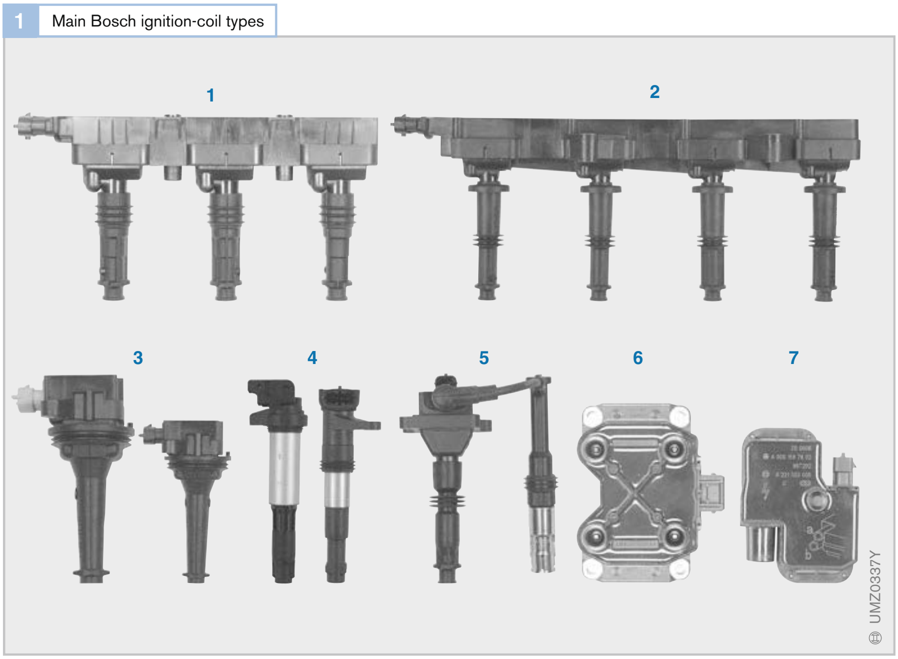

Fig. 1
1 Module with three single-spark coils
2 Module with four single-spark coils
3 Single-spark coil (compact coil)
4 Single-spark coil (pencil coil)
5 Dual-spark coil (one magnetic circuit)
6 Dual-spark coil with two magnetic circuits (four high-voltage domes)
7 Module with two single-spark coils

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Examples:

- To ensure secure and reliable ignition of the mixture under all conditions, turbocharged engines need more spark energy than manifold-injection engines; engines with gasoline direct injection have the highest energy requirement of all.
- Spark current has a relatively limited effect on the service life of modern-day spark plugs.
- Turbo- and supercharged engines need consistently higher ignition voltages than non-charged engines.
- The ignition driver stage and the ignition coil must be mutually matched for correct configuration of the operating point (primary current).
- The connection between the ignition coil and the spark plug must be designed for safe and reliable performance under all conditions (voltage, temperature, vibration, resistance to aggressive substances).

Areas of application

Ignition coils made their debut in Bosch ignition systems when battery-based ignition replaced magneto ignition in the 1930s. Since then, they have been subject to ongoing improvements while being adapted to various new areas of applications. Coils are used in all vehicles and machines equipped with inductive ignition systems.

Requirements

Emission-control legislation imposes limits on pollutant emissions from internal-combustion engines. Ignition misses and incomplete mixture combustion, which lead to rises in HC emissions, must be avoided. It is thus vital to have coils that consistently provide adequate levels of ignition energy throughout their service lives.

In addition to these considerations, coils must also suit the geometry and design configuration of the engine. Earlier ignition systems with rotating high-voltage distribution (distributor, [asphalt] ignition coil, ignition cables) featured standardized coils in for mounting on the engine or the vehicle body.

The ignition coil is subject to severe performance demands – electrical, chemical and mechanical – yet still expected to provide fault- and maintenance-free operation for the entire life of the vehicle. Depending on where they are installed in the vehicle – often directly in the cylinder head – today's ignition coils must be able to operate under the following conditions:

- Operating-temperature range of −40...+150 °C
- Secondary voltage up to 30,000 V
- Primary current between 7 and 15 A
- Dynamic vibration loading up to 50 g
- Durable resistance to various substances (gasoline, oil, brake fluid, etc.)

Design and method of operation

Design

Primary and secondary windings

The ignition coil (Fig. 1, Pos. 3) operates in accordance with the principle of a transformer. Two windings surround a shared iron core.

The primary winding consists of thick wire with a relatively low number of turns. One end of the winding is connected to the battery's positive terminal (1) via the ignition switch (terminal 15). The other end (terminal 1) is connected to the ignition driver stage (4) to control the flow of primary current.

Although contact-breaker points were still being used to control primary current as late as the end of the 1970s, this arrangement is now obsolete.

The secondary winding consists of thin wire with a larger number of turns. The turns ratio usually ranges between 1:50 and 1:150.

In the basic economy circuit (Fig. 2a), one terminal from the primary winding is connected to one terminal on the secondary winding, and these are both linked to terminal 15 (ignition switch). The other end of the primary winding is connected to the ignition driver stage (terminal 1). The secondary winding's second terminal (terminal 4) is connected to the ignition distributor or to the spark plug. The autotransformer principle makes the coil less expensive thanks to the common terminal at terminal 15. But because there is no mutual electrical isolation between the two electric circuits, electrical interference from the coil can be propagated into the vehicle's electrical system.

The primary and secondary windings are not interconnected in Figs. 2b and 2c. On the single-spark coil, one side of the secondary winding is connected to ground (terminal 4a), while the other side (terminal 4) leads directly to the spark plug. Both of the secondary-winding connections on the dual-spark ignition coil (terminals 4a and 4b) lead to a spark plug.

1 Principle of high-voltage generation with the ignition coil

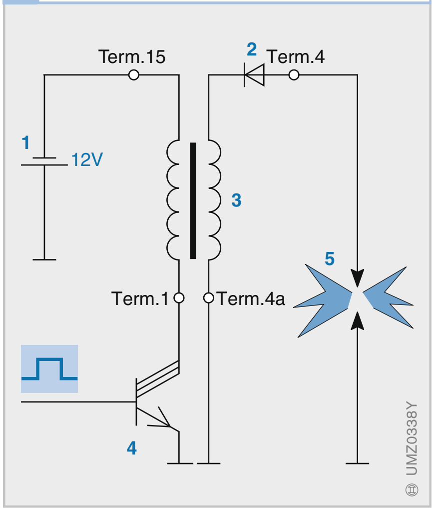


Fig. 1
1 Battery
2 AAS diode (integrated in ignition coil)
3 Coil with iron core and primary and secondary windings
4 Ignition driver stage (alternatively integrated in Motronic ECU or in ignition coil)
5 Spark plug

Term. 1, Term. 4, Term. 4a, Term. 15
Terminal designations

2 Schematic representation of ignition coils

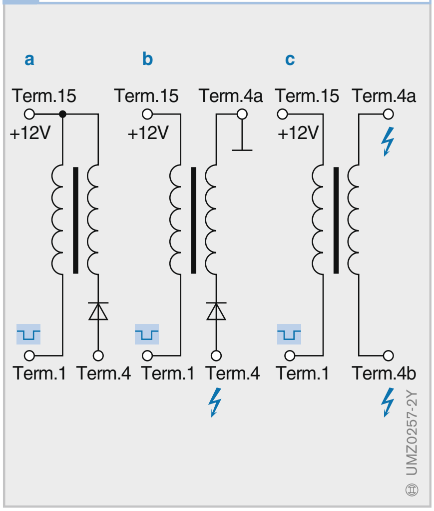


Fig. 2
a Single-spark coil in economy circuit (AAS diode not required on ignition systems with rotating high-voltage distribution)
b Single-spark ignition coil
c Dual-spark ignition coil

Operating principle

High-voltage generation

The engine ECU activates the ignition driver stage for the calculated dwell period. During this period, the coil's primary current climbs to the setpoint level to generate a magnetic field.

The level of the primary current and the coil's primary inductance determine the amount of energy stored in the magnetic field.

At the moment of ignition (ignition point), the ignition driver stage interrupts the current flow. The resulting shift in the magnetic field induces secondary voltage in the coil's secondary winding. The maximum possible secondary voltage (secondary-voltage supply) is dependent on the energy stored in the ignition coil, the winding capacitance, the coil's turns ratio, the secondary load (spark plug), and the primary-voltage limitation (clamp voltage) of the ignition driver stage.

The secondary voltage must in any case exceed the voltage level required for flashover at the spark plug (ignition-voltage demand). The spark energy must be sufficiently high to ignite the mixture even when follow-up sparks are generated. Follow-up, or secondary, sparks occur when the ignition spark is deflected by turbulence in the mixture and breaks away.

When the primary current is activated, an undesired voltage of roughly 1...2 kV is induced in the secondary winding (switch-on voltage); its polarity is opposed to that of the high voltage. A flashover at the spark plug (switch-on spark) must be avoided.

In systems with rotating high-voltage distribution, the switch-on spark is effectively suppressed by the upstream distributor spark gap. In systems with distributorless (stationary) voltage distribution with single-spark ignition coils, a diode (AAS diode, see Figs. 2 a and 2 b) suppresses the switch-on spark in the high-voltage circuit. This AAS diode can be installed on the "hot" side (facing toward the spark plug) or the "cold" side (facing away from the spark plug).

In systems with dual-spark coils, the switch-on spark is suppressed by the high flashover voltage in the series circuit feeding the two spark plugs without additional measures.

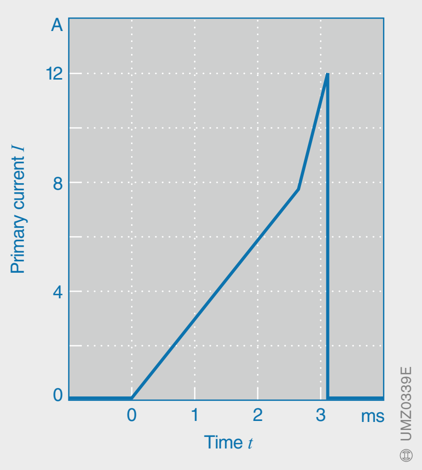
Deactivating the primary current produces a self-induction voltage of several hundred volts in the primary winding. To protect the driver stage, this is limited to 200...400 V.

Generating the magnetic field

A magnetic field is generated in the primary winding as soon as the driver stage completes the circuit. Self-induction creates an inductive voltage in this winding, which according to Lenz's law opposes the cause – i.e., the generation of the magnetic field. This rule explains why the rate at which the magnetic field is generated is always comparatively low (Fig. 3) in relation to the iron cross-section and the winding (inductance).

The primary current will continue to rise while the circuit remains closed; beyond a certain current flow, magnetic saturation occurs in the magnetic circuit. The actual level is determined by the ferromagnetic material used. Inductance falls and current flow rises more sharply. Losses within the ignition coil

3 Primary-current curve in the ignition coil



also rise steeply. It is therefore sensible to have the operating point as far as possible below the magnetic-saturation level. This is determined by means of the dwell period.

Magnetization curve and hysteresis

The ignition coil's core consists of a soft-magnetic material (in contrast, permanent magnets are hard-magnetic material). This material displays a characteristic magnetization curve that defines the relationship between the magnetic field strength *H* and the flux density *B* within it (Fig. 4). Once maximum flux density is reached, the effect of additional increases in field strength on flux density will be minimal: saturation has occurred.

Yet another property of this material is hysteresis in the magnetization curve. This material property denotes a situation where the flux density (i.e., the magnetization) is dependent not only on the currently effective field strength but also on the earlier magnetic state. The magnetization curve assumes a different shape in the case of magnetization (increasing field strength) than it does in the case of demagnetization (decreasing field strength). The intrinsic losses in the material used are proportional to the level of hysteresis. The area included by the hysteresis curve is a measure of the intrinsic losses.

Magnetic circuit

The material most commonly used in ignition coils is electrical sheet steel, processed in various layer depths and to various specifications. Depending on what is required of it, the material is either grain-oriented (high maximum flux density, expensive) or non-grain-oriented (low maximum flux density).

Sheet metal with layer depths of 0.3...0.5 mm is most commonly used. Mutually insulated plates are used to reduce eddy-current losses. The plates are stamped, combined in plate packs and joined together; this process provides the required thickness and geometrical shape.

The best possible geometry for the magnetic circuit must be defined to obtain the desired electrical performance data for an ignition coil from any given coil geometry.

4 Magnetization curve with hysteresis curve

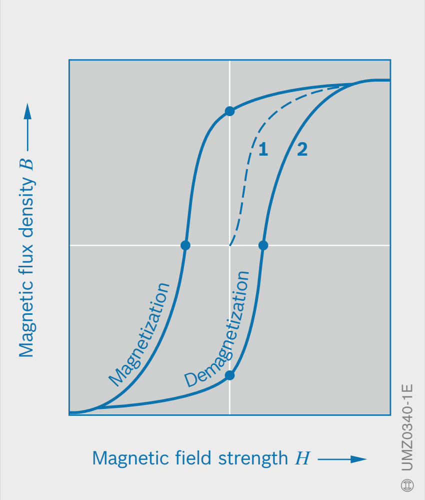


Fig. 4
1 New curve (magnetization curve of demagnetized iron core)
2 Hysteresis curve

5 Magnetic circuit in compact coil with O and I cores

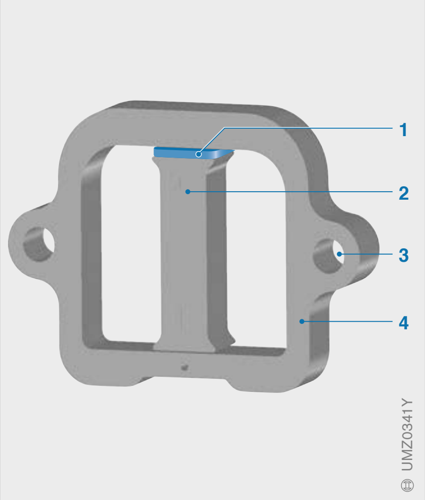


Fig. 5
1 Air gap or permanent magnet
2 I core
3 Fastening hole
4 O core

To meet the electrical requirements (spark duration, spark energy, secondary-voltage rise, secondary-voltage level), an air gap is needed which effects a shear in the magnetic circuit (Fig. 5, Pos. 1). A larger air gap (greater shear) permits a higher magnetic field strength in the magnetic circuit and thus leads to a higher magnetic energy that can be stored. This substantially raises the current levels at which magnetic saturation occurs in the magnetic circuit. Without this air gap, saturation would occur at low currents, and subsequent rises in current flow would produce only insignificant increases in levels of stored energy (Fig. 6).

What is important here is that the overwhelming proportion of the magnetic energy is stored in the gap.

In the coil-development process, FEM simulation is employed to define the dimensions for the magnetic circuit and the air gap that will provide the required electrical data. The object is to obtain ideal geometry for maximum storable magnetic energy for a given current flow without saturating the magnetic circuit.

6 Shear in magnetic circuit

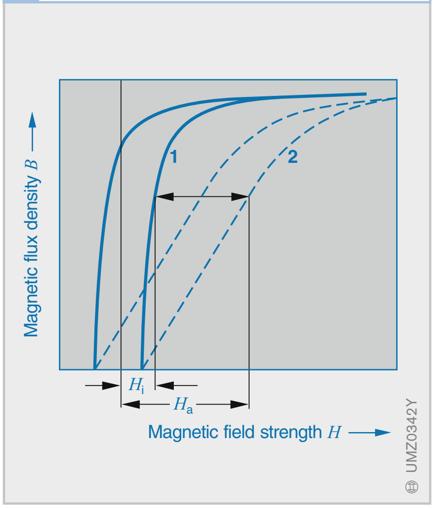


Fig. 6
1 Hysteresis for iron core without air gap
2 Hysteresis for iron core with air gap

H_i Modulation for iron core without air gap
H_a Modulation for iron core with air gap

It is also possible to respond to the requirements associated with limited installation space, especially important with pencil coils, by installing permanent magnets (Fig. 5, Pos. 1) to increase the magnetic energy available for storage. The permanent magnet's poles are arranged to allow it to generate a magnetic field opposed to the field in the winding. The advantage of this premagnetization lies in the fact that more energy can be stored in this magnetic circuit.

Switch-on sparks

Activating the primary current changes the current gradients to produce a sudden shift in magnetic flux in the iron core. This induces voltage in the secondary winding. Because the gradient for the current change is positive, the polarity of this voltage polarity is opposed to that of the induced high voltage when the circuit is switched off. Because this gradient is very small relative to the gradients that occur when the primary current is deactivated, the induced voltage is relatively low, despite the large turns ratio arising from the disparity in turn numbers between the two windings. It lies within a range of 1...2 kV, and could be enough to promote spark generation and mixture ignition under some conditions. To prevent possible engine damage, preventing a flashover (switch-on spark) at the spark plug is vital.

In systems with rotating high-voltage distribution, this switch-on spark is suppressed by the upstream distributor spark gap. The rotor-arm contact is not directly across from the cap contact when activation occurs.

In systems with distributorless (stationary) voltage distribution and single-spark ignition coils, the AAS diode (**A**ctivation **A**rc **S**uppression) suppresses the switch-on spark (see Fig. 1, Pos. 2). With dual-spark coils, the switch-on spark is suppressed by the high flashover voltage of the series circuit with its two spark plugs, and no supplementary measures are required.

Heat generation in the coil

The efficiency, defined as the available secondary energy relative to the stored primary energy, is on the order of 50...60 %. Under certain boundary conditions, high-performance ignition coils for special applications can achieve efficiency levels as high as 80 %.

The difference in energy is primarily converted into heat through the resistance losses in the windings as well as remagnetization and eddy-current losses.

A driver stage integrated directly in the coil can represent yet another source of thermal loss. The primary current causes a voltage drop in the semiconductive material, leading to lost efficiency. A further and thoroughly significant energy loss is attributable to the switching response when the primary current is deactivated, especially when the driver stage is “slow” in its dynamic response.

High secondary voltages are usually limited by the restriction on primary voltage in the driver stage, where part of the energy stored in the coil is dissipated as thermal loss.

Capacitive load

Capacitance in the ignition coil, the ignition cable, the spark-plug well, the spark plug, and adjacent engine components is low in absolute terms, but remains a factor of not inconsiderable significance in view of the high voltages and voltage gradients. The increased capacitance reduces the rise in secondary voltage. Resistive losses in the windings are higher, high voltage is reduced.
In the end, all of the potential secondary energy is not available to ignite the mixture.

Spark energy

The electrical energy available for the spark plug within the ignition coil is called spark energy. It is an essential criterion in ignition-coil design; depending on the winding configuration, it determines such factors as the spark current and the spark duration at the spark plug.

Spark energies of 30...50 mJ are the norm for igniting mixtures in naturally aspirated and turbocharged engines. A higher spark energy (up to 100 mJ) is needed for safe and reliable ignition at all engine operating points in engines with gasoline direct injection.

Ignition-coil types

Single-spark ignition coil

Each spark plug has its own ignition coil in systems with single-spark ignition coils.

The single-spark coil generates one ignition spark per power stroke via the spark plug. It is thus necessary to synchronize operation with the camshaft in these systems.

Dual-spark ignition coil

Single-spark ignition (one spark plug per cylinder)
The dual-spark coil generates ignition voltage for two spark plugs simultaneously. The voltage is distributed to the cylinders in such a way that

- The air/fuel mixture in the one cylinder is ignited at the end of the compression stroke
- The ignition spark in the other cylinder is generated during the valve overlap at the end of the exhaust stroke

The dual-spark coil generates a spark for every crankshaft rotation, corresponding to twice for each power stroke. This means that no synchronization with the camshaft is required with this ignition system. However, this ignition coil can only be used in engines with an even number of cylinders.

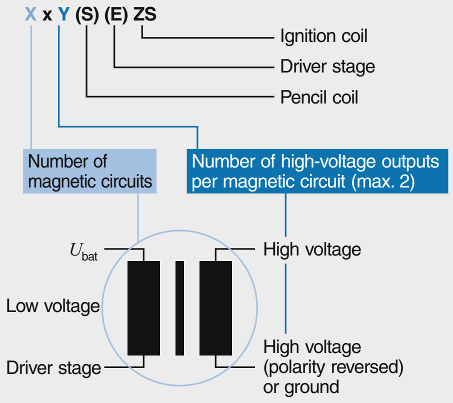
There is no compression within the cylinder at the point of valve overlap, and the flashover voltage at the spark plug is therefore very low. This "additional or maintenance spark" therefore requires only very small amounts of energy for flashover.

Dual-plug ignition
In ignition systems with two spark plugs per cylinder, the ignition voltages generated by one ignition coil are distributed to two different cylinders. The resulting advantages are

- Emissions reductions
- A slight increase in power
- Two sparks at different points in the combustion chamber
- The option of using ignition offset to achieve "softer" combustion
- Good emergency-running characteristics when one ignition coil fails due to a fault

Bosch coil designations

Terminology



Examples

ZS-P(E)	Pencil coil (with integ. driver stage)
2x2 ZS	Ignition coil with • 2 magnetic circuits • 2 sparks per circuit … with 4 high-voltage terminals
4x1 ZS	Module with 4 separate single-spark coils

Bosch has introduced these designations to rationalize its type definitions

Types

Virtually all of the coils in the ignition systems being designed today are either

- Compact coils, or
- Pencil coils

It is also possible to integrate the ignition driver stage within the housing on some of the coil models described in the following.

Compact ignition coil

Design

The compact coil's magnetic circuit consists of the O core and the I core (Fig. 1), onto which the primary and secondary windings are plugged. This arrangement is installed in the coil housing. The primary winding (I core wound in wire) is electrically and mechanically connected to the primary plug connection. Also connected is the start of the secondary winding (coil body wound in wire). The connection on the spark-plug side of the secondary winding is also located in the housing, and electrical contacting is established when the windings are fitted.

Integrated within the housing is the high-voltage contact dome. This contains the contact section for spark-plug contacting, and also a silicone jacket for insulating the high voltage from external components and the spark-plug well.

Once the components have been assembled, impregnating resin is vacuum-injected into the inside of the housing, where it is allowed to harden. This process provides

- High resistance to mechanical loads
- Effective protection against environmental factors, and
- Excellent insulation against high voltage

The silicone jacket is then pushed onto the high-voltage contact dome for permanent attachment.

The ignition coil is ready for use after it has been tested to ensure compliance with all the relevant electrical specifications.

1 Compact-ignition-coil design

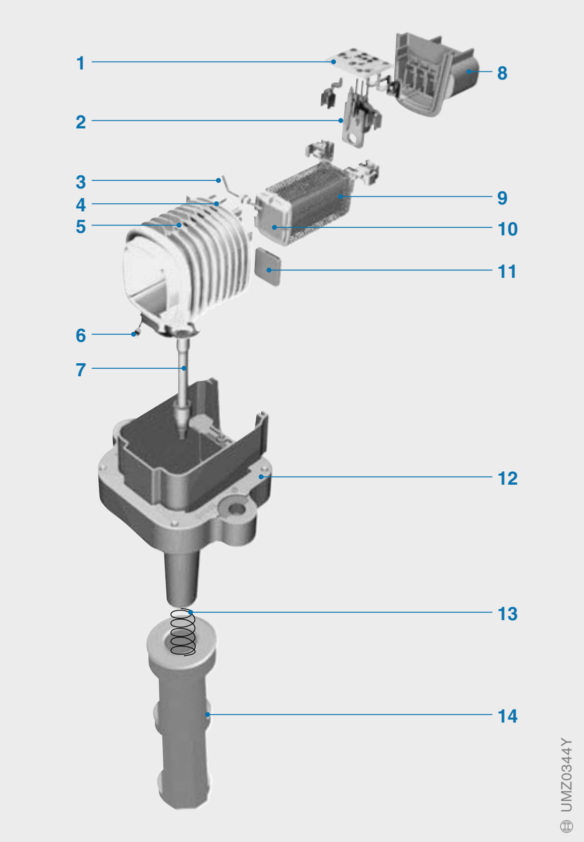


Fig. 1
1 Printed-circuit board
2 Ignition driver stage
3 AAS diode
4 Secondary coil element
5 Secondary wire
6 Contact plate
7 High-voltage pin
8 Primary plug
9 Primary wire
10 I core
11 Permanent magnet
12 O core
13 Spring
14 Silicone jacket

Remote and COP versions

The ignition coil's compact dimensions make it possible to implement the design shown above in Figure 1. This version is called COP (**C**oil **o**n **P**lug). The ignition coil is mounted directly on the spark plug, thereby rendering additional high-voltage connecting cables superfluous (Fig. 2a). This reduces the capacitive load on the coil's secondary winding. The reduction in the number of components also increases operational reliability (no rodent bites in ignition cables, etc.).

In the less common remote version, the compact coils are mounted within the engine compartment using screws. Attachment lugs or an additional bracket are provided for this purpose. The high-voltage connection is effected by means of a high-voltage ignition cable from the coil to the spark plug.

The COP and remote versions are virtually identical in design. However, the remote version (mounted on the vehicle body) is subject to fewer demands with regard to temperature and vibration conditions due to the fact that it is exposed to fewer loads and strains.

Other coil types

ZS 2x2

Rotating high-voltage distribution is being gradually superseded by distributorless (stationary) voltage distribution.

An uncomplicated means for converting an engine model to distributorless distribution is offered by the ZS 2x2 (Fig. 3) and the ZS 3x2 (German: Zündspule = ignition coil, hence ZS). These ignition coils contain two (or three) magnetic circuits, and generate two sparks per circuit. They can thus be used to replace the distributors in four- and six-cylinder engines. Because the units can be mounted almost anywhere in the engine compartment, the vehicle manufacturer's adaptation effort is minimal, although the engine ECU has to be modified. Another factor is that high-voltage ignition cables are required in most cases for layouts with remote ignition coils.

2 Single-spark coils

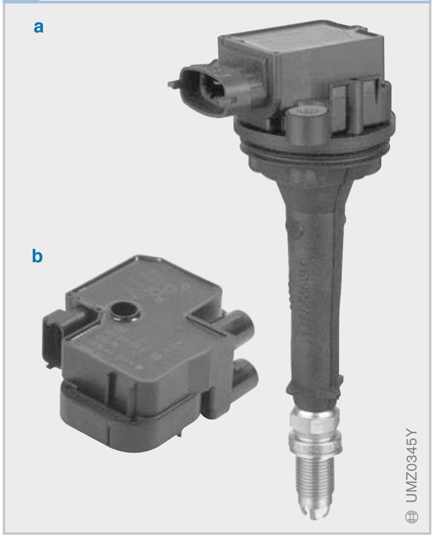


Fig. 2
a COP version of a single-spark compact coil
b Remote version: two single-spark coils in module, spark plugs connected via two ignition cables

3 2x2 ignition coil for converting from rotating to distributorless voltage distribution

Ignition-coil modules

Ignition-coil modules combine several coils in a shared housing to form a single assembly (Fig. 4). These coils continue to operate individually.

The advantages furnished by coil modules are

- Simplified installation (just a single operation for three or four ignition coils)
- Fewer threaded connections
- Connection to the engine wiring harness with just one plug
- Cost savings thanks to faster installation and simplified wiring harness

Disadvantages:

- It is necessary to adapt the module's geometry to fit the engine, and
- Modules must be designed to fit individual cylinder heads; no universal designs

Pencil coil

The pencil coil makes optimal use of the space available within the engine compartment. Its cylindrical shape makes it possible to use the spark-plug well as a supplementary installation area for ideal space utilization on the cylinder head (Fig. 5).

Because pencil coils are always mounted directly on the spark plug, no additional high-voltage connecting cables are required.

Design and magnetic circuit

Pencil coils operate like compact coils in accordance with the inductive principle. However, the rotational symmetry results in a design structure that differs considerably from that of compact coils.

Although the magnetic circuit consists of the same materials, the central rod core (Fig. 6, Pos. 5) consists of laminations in various widths stacked in packs that are virtually spherical. The yoke plate (9) that

4 Ignition-coil modules with compact coils

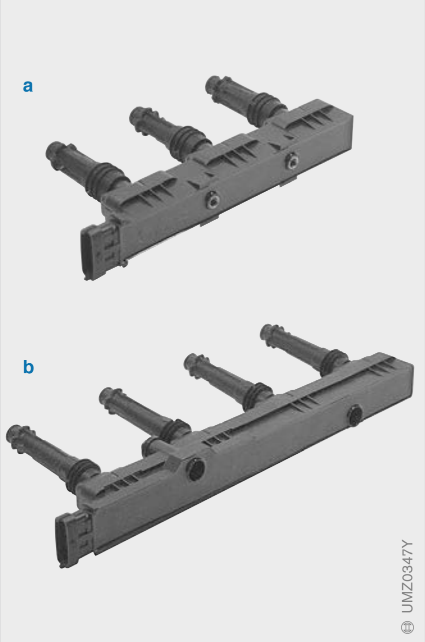


Fig. 4
a ZS 3x1M
b ZS 4x1M

5 Installation in spark-plug well: relative dimensions of compact and pencil coils

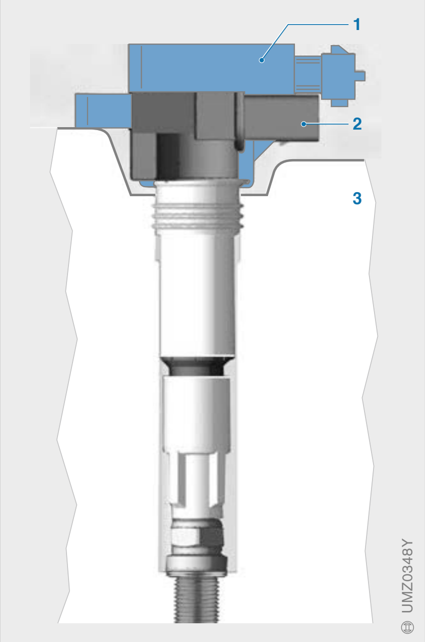
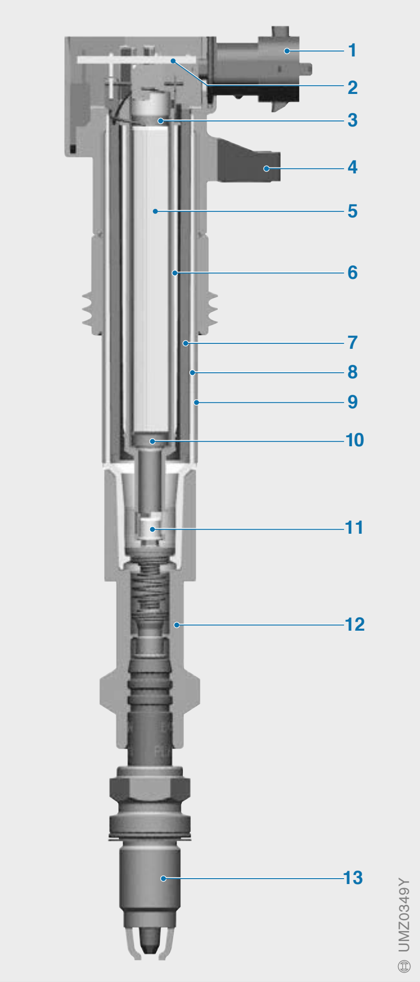


Fig. 5
1 Compact coil
2 Pencil coil
3 Cylinder head

provides the magnetic circuit is a rolled and slotted shell – also in electrical sheet steel, sometimes in multiple layers.

Another difference relative to compact coils is the primary winding (7), which has a larger diameter and is above the secondary winding (6), while the body of the winding also supports the rod core. This arrangement brings benefits in the areas of design and operation.

6 Design of pencil coil



Owing to restrictions imposed by their geometrical configuration and compact dimensions, pencil coils allow only limited scope for varying the magnetic circuit (rod core, yoke plate) and windings.

In most pencil-coil applications, the limited space available dictates that permanent magnets be used to increase the spark energy.

The arrangements for electrical contact with the spark plug and for connection to the engine wiring harness are comparable with those used for compact coils.

Variants

An extended range of variants (e.g., different diameters and lengths) is available to provide pencil coils for assorted applications. The ignition driver stage can also be integrated within the housing as an option.

A typical diameter, as measured at the cylindrical center section (yoke plate, housing), is roughly 22 mm. This dimension is derived from the hole diameter of the spark-plug well within the cylinder head as used with standard spark plugs featuring a 16 mm socket fitting. The length of the pencil coil is determined by the installation space in the cylinder head and the required or potential electrical performance specifications. Extending the active section (transformer) is subject to limits, however, due to the parasitic capacitance and the deterioration of the magnetic circuit involved.

Fig. 6

1 Plug connection
2 Printed-circuit board with ignition driver stage
3 Permanent magnet
4 Attachment arm
5 Laminated electrical-sheet-steel core (rod core)
6 Secondary winding
7 Primary winding
8 Housing
9 Yoke plate
10 Permanent magnet
11 High-voltage dome
12 Silicone jacket
13 Attached spark plug

Cavities filled with sealing compound

Ignition-coil electronics

In earlier designs, the ignition driver stage was usually incorporated within a separate module, and attached to the coil or the distributor within the engine compartment of a vehicle with rotating voltage distribution. The conversion to distributorless ignition combined with increasing miniaturization of electronic componentry to foster the development of ignition driver stages embedded in integrated circuits and thus suitable for incorporation in the ignition or engine ECUs.

The constantly increasing functional scope of engine ECUs (Motronic) and new engine concepts (e.g., gasoline direct injection) have increased thermal stresses (overall heat loss from driver stages) and reduced installation space. These factors have produced a trend toward remote driver stages located outside the ECU. One option is integration within the ignition coil, which also makes it possible to use a shorter primary wire to reduce line loss.

Design

The driver stage can be integrated in the housing of both compact and pencil coils. Figure 1 shows installation in a pencil coil. The driver-stage module – which can also incorporate additional functions – is mounted on a small printed-circuit board. SMD (Surface Mounted Device) components are used because of the restricted dimensions.

The driver-stage transistors (7) are integrated in standardized TO housings and connected to the circuit board or conductor rails. Additional functions for monitoring, diagnosis or other functions (e.g., closed-circuit current deactivation, customer-specific input circuit) can be optionally integrated in further electronic components (3). The primary connector (1) is connected directly to the circuit board. Below the board are the contacts for the coil's primary winding (4).

1 Installation of the driver stage in a pencil-coil housing

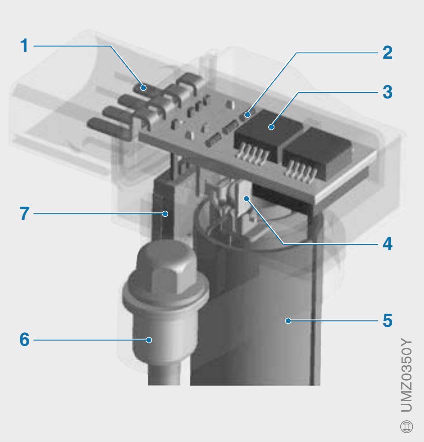


Fig. 1
1 Primary plug
2 SMD components
3 Electronics for ignition functions
4 Primary winding contacts
5 Pencil-coil transformer
6 Attachment lug
7 Driver stage

Electrical parameters

Inductance

Inductance is a physical variable which denotes the electromagnetic efficiency or self-induction capability of a coil or, in general, of an electrical conductor.

Inductance is determined by the material and cross-section of the permeated magnetic circuit, the number of windings, and the geometry of the copper winding.

An ignition coil includes primary and secondary inductance elements, with the secondary inductance being many times greater.

Capacitance

Three different types are encountered in an ignition coil: inherent capacitance, parasitic capacitance and load capacitance. Inherent capacitance of an ignition coil is essentially created by the winding itself. It is created from the fact that neighboring wires within the secondary winding form a capacitor.

Parasitic capacitance is a “harmful” capacitance within an electrical system. Part of the available or generated energy is needed to charge or recharge this parasitic capacitor and is therefore not available at the connections. In an ignition coil, parasitic capacitance is created, for example, by the small gap between the secondary and primary windings or by cable capacitance between ignition cable and neighboring components.

Load capacitance is essentially created by the spark plug. It is determined by the installation environment (e.g., metallic spark-plug well), the spark plug itself, and any high-voltage connecting cables that may be present. These factors are not usually subject to modification and must be taken into consideration in the design of the ignition coil.

1 Parameters for ignition coils (series application)

I_1	Primary current	6.5...9.0 A
T_1	Charging time	1.5...4.0 ms
U_2	Secondary voltage	29...35 kV
T_{sp}	Spark duration	1.3...2.0 ms
W_{sp}	Spark energy	30...50 mJ, up to 100 mJ for gasoline direct injection
I_{sp}	Spark current	80...115 mA
R_1	Resistance of primary winding	0.3...0.6 Ω
R_2	Resistance of secondary winding	5...15 kΩ
N_1	Number of turns in primary winding	150...200
N_2	Number of turns in secondary winding	8000...22,000

Stored energy

The amount of magnetic energy that can be stored depends upon numerous factors such as the coil’s design (geometry, material in the magnetic circuit, additional magnets) and the ignition driver stage used. Once a certain point is reached, any additional increases in primary current will deliver only minimal rises in stored energy, while losses grow disproportionately, ultimately leading to destruction of the coil within a short period of time.

While taking into account all the tolerances, the ideal coil thus operates just below the magnetic circuit’s magnetic saturation point.

Resistance

The resistance of the windings is determined by the temperature-sensitive specific resistance of copper.

The primary resistance (resistance of the primary winding) is normally within the range of 0.4...0.7 Ω. It should not be too high, because in the event of low vehicle system voltage (voltage dip during cold starting) the ignition coil would not reach its rated current, and would thus not be able to generate a lower spark energy.

The secondary resistance (resistance of the secondary winding) is in the range of several kΩ; it differs from the primary resistance in the larger number of turns on the secondary winding (by a factor of 70...100) and the small wire diameter (by a factor of approximately 10).

Power loss

The losses in an ignition coil are determined by resistance in the windings, capacitive losses and remagnetization losses (hysteresis), as well as by construction-necessitated deviations from the ideal configuration for a magnetic circuit. At an efficiency level of 50...60 %, relatively high power losses are generated in the form of heat at high engine speeds. The losses are kept as low as possible by loss-minimized configurations, suitable design solutions, and materials subject to high thermal loads.

Turns ratio

The turns ratio is the ratio of the number of turns in the primary copper winding to the number in the secondary copper winding. On standard ignition coils, it is on the order of 1:50...1:150. Determination of the turns ratio is used in combination with driver-stage specifications to affect such factors as the level of spark current and – to some degree – the maximum secondary voltage.

High-voltage and spark-generation properties

The ideal coil remains relatively impervious to load factors while producing as much high voltage as possible within an extremely brief rise period. These properties ensure flashover at the spark plug for reliable mixture ignition under all conditions encountered in operation.

At the same time, the real-world properties of the windings, the magnetic circuit and the driver stage used all unite to impose limits on performance.

The polarity of the high voltage ensures that the spark plug's center electrode maintains negative potential relative to chassis ground. This negative polarity counteracts the tendency of the spark plug's electrodes to erode.

Dynamic internal resistance

Yet another important parameter is the coil's dynamic internal resistance (impedance). Because impedance combines with internal and external capacitance to help determine voltage rise times, it serves as an index of the amount of energy that can flow from the coil and through shunt-resistance elements at the moment of flashover. Low internal resistance is an asset when spark plugs are contaminated or wet. Internal resistance depends on secondary inductance.

Simulation-based development of ignition coils

Ever-increasing technical demands mean that the efficiency limits of conventional design and development methods are reached early. Product-development processes using CAE provide a solution. CAE (**C**omputer **A**ided **E**ngineering) is the generic term for computer-based engineering services. It includes all aspects of CAD (**C**omputer **A**ided **D**esign) as well as calculation routines.

The advantages offered by CAE are:

- Informed decisions at early stages in the development process (also without prototypes)
- Identification of specimens suitable for testing, and
- Enhanced understanding of physical interrelationships

Calculation programs are employed in various areas of simulation in ignition-coil development:

- Structural mechanics (analysis of mechanical and thermal stress factors)
- Fluid mechanics (analysis of fluidic charging processes)
- Electromagnetics (analysis of the system's electromagnetic performance)

Electromagnetic simulation tools are especially important in the development ignition coils. Two different types of simulation may be used here: geometry-orientated simulation and performance simulation.

The **F**inite **E**lement **M**ethod (FEM) is used with geometry-orientated simulation. Here, the coil's geometry is modeled on the basis of a CAD model. This is provided with appropriate boundary conditions (current density, electrical potential, etc.) and then converted into an FEM model. Transfer to a calculation model and derivation of specifications from the corresponding equation series follow. The result is a clear calculated solution to the problem.

This method permits 100 % virtual, simulation-based ignition-coil design. Depending on the analysis objective, it is possible here to optimize the geometry of the ignition coil (magnetic optimization of the magnetic circuit, electrostatic optimization of electrically conductive contours).

Following geometry-orientated analysis, performance simulation can be employed to examine the coil's electrical characteristics within the overall system, consisting of driver stage, coil and spark plug, under conditions reflecting the actual, real-world environment. This calculation method provides the initial specification data for the coil. It also supports subsequent calculation of electrical parameters such as spark energy and spark current.

Electromagnetic simulation tools make "virtual" development of ignition coils possible. The simulation results define geometrical data and winding design to furnish the basis for specimen construction. The electrical performance of these specimen coils will approximate the simulation results. This substantially reduces the number of time-consuming recursion processes that occur when coils are produced using conventional product-development methods.