7.3 New Developments and Optimization of The Advanced Corona Ignition System (ACIS)

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Abstract

This paper describes the application of modelling and experimental methods to the development of igniters for a corona ignition system. Steps are described to address the problems typically encountered when designing such an igniter, including electrical, thermal, and durability concerns. Solutions are presented for “streamer” designs in which corona propagates freely in space through the combustion chamber, leading to excellent ignition. In addition, novel solutions are presented for “barrier discharge ignition” (BDI) igniters which allow many of the drawbacks formerly encountered with this igniter type to be avoided.

1 State of the Art

Corona ignition systems have been tested since the 1960s in a wide variety of designs, but can be divided into four broad groups, here assigned the following descriptive names:

1. Arc design: a high frequency electric field causes an arc-like plasma to be formed between two electrodes, either in free air or over a surface or a combination of both. Arc formation is encouraged and arc current is limited by the driving circuit.
2. Steamer design: a high frequency electric field, locally much higher than the global value, causes streamers of branching corona discharge spreading out directly from the electrode into the surrounding air towards the grounded metal engine. System geometry is chose to minimize or avoid arc formation.
3. Barrier Discharge (BDI) design: an insulator completely surrounds the high voltage electrode and prevents the possibility of arc formation. High frequency electric field penetrates this insulator and causes corona discharge in the air around the plug.
4. Pulse design: application of a pulse of high voltage causes a plasma between the high voltage electrode and either the structure of the engine or a second electrode designed for this purpose. Duration of the pulse is controlled such that the time available is too short for arc formation.

1.1 Arc Design Igniters

Arc igniters may be represented by the design shown in Figure 1 [1]. In this case the central electrode is energised with a high voltage of moderate frequency (kilohertz to megahertz), and this ionises the air between the electrodes, here over the surface of the insulator to create a Projected Surface Discharge (PSD) design.

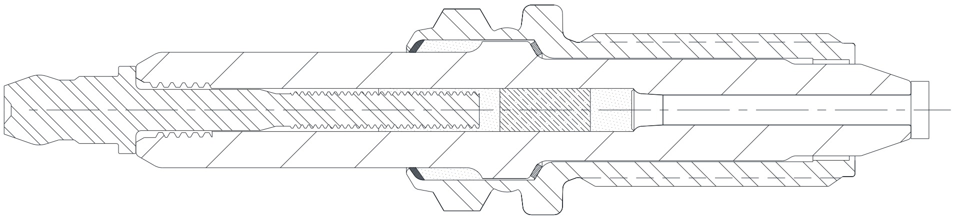


Figure 1: Exemplary design of an arc igniter.
Reference [1]

This type of system is also applicable to conventional sparkplug design and may be used to generate an ignition event of arbitrary duration or power. This has the following desirable features for ignition:

- Duration and current of the event are arbitrary, set by the drive circuit.
- The high frequency along with optional formation over an insulator surface, as in the case of the example in the figure, allows a wider spacing between electrodes and hence an ignition source of larger spatial extent than would be possible with conventional inductive or CDI ignition.
- Damage to the electrodes may be controlled by modulating the voltage and current applied.
- Installation requirements are trivial as the corona is only formed at locations within the control of the plug designer and hence within a well-defined envelope.

However, the following limitations are observed:

- Only one path is energised at a time, as the low-conductivity arc shunts all available energy in a single channel. A single arc path may tend to persist across many cycles of the drive voltage; although it may form new arc paths periodically, only one is energised at a time. Hence spatial extent of the ignition source is limited.
- Flame propagation may be limited by proximity to the insulator surface in some designs.
- Wear of the electrodes may be reduced but cannot be eliminated because significant current still flows between electrode surfaces.
- Many designs have thermal difficulties at high load due to the large exposed central electrode area, coupled with the long projection of the insulator required to achieve the correct spark position.
- Surface discharge designs provide the largest possible ignition source but may suffer from cold fouling problems due to carbon shunting. Addition of an air gap mitigates this problem but leads to a large rise in required voltage.

1.2 Streamer Design Igniters

This type of igniter, shown in Figure 2 [2], has a high frequency (megahertz to tens of megahertz), high voltage electrode configured to give a local electric field which is higher than the global field.

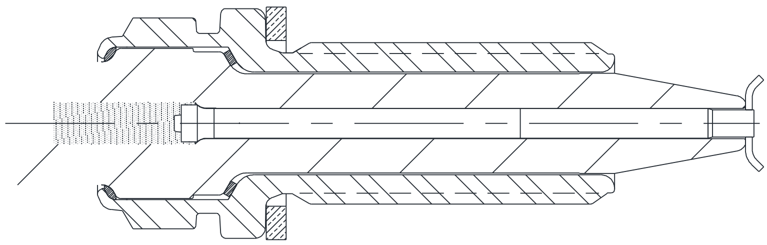


Figure 2: Exemplary design of a streamer igniter Reference [2].

High field close to this electrode causes ionization of the local air and this ionization spreads out in a branching pattern away from the electrode. This has the following beneficial results:

- Large spatial extent of the branching corona.
- Persistence of the streamers: in contrast to the arc design where only one path exists at a time, multiple steamers may simultaneously form and be maintained and even grow throughout the ignition event.
- This gives multiple ignition sources far from combustion chamber surfaces.
- Current from the electrodes is small unless an arc is formed. Electrode life is not impacted by electrical erosion.
- Energy transfer from corona to gas is very good, leading to improved overall system efficiency.

Amongst the drawbacks are:

- A locally high electric field is required, which is often achieved by using sharp electrode tips. These are difficult to cool adequately and may be subject to corrosion in operation.
- If the corona streamer reaches a grounded engine component, an arc will form which reduces ignition quality and can lead to electrode damage over time. Adequate space is needed around the igniter and this can limit compression ratio.
- Following from the point above, if the electrode is close to a grounded surface (for example the piston at TDC) then the peak local field is comparable to the average field and a corona streamer will never form, or will break down immediately into an arc.
- Careful control of the applied energy is required in order to avoid arcing and the associated drop in ignitability. This requires additional content in the control electronics and additional calibration effort.

1.3 Barrier Discharge Ignition (BDI)

Barrier discharge igniters, such as represented in Figure 3, exist in several different formats. They typically use a high voltage electrode driven with a high frequency (megahertz to tens of megahertz).

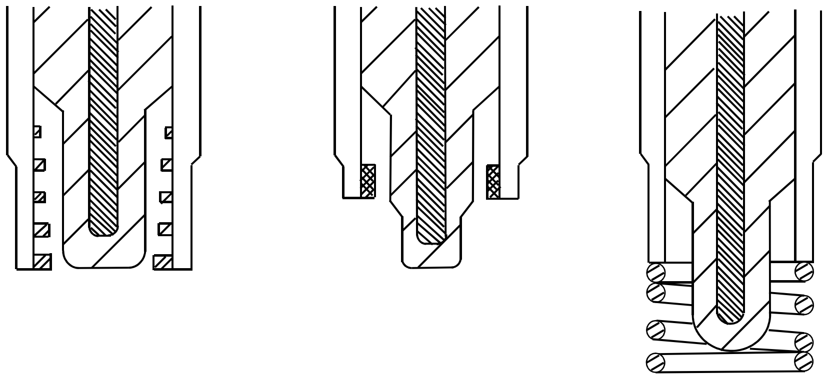


Figure 3: Exemplary designs of a Barrier Discharge Igniter (BDI). From Left to right, Figures 3.1, 3.2 and 3.3 References [3] and [4].

Figure 3.1 [3] shows a design where the high voltage electrode is surrounded by a largely cylindrical insulator, with a cylindrical ground element spaced from this. An annular corona discharge is formed due to the high electric field formed between the insulator surface and the ground. Features on the ground, insulator or (with less effect) the central electrode may be added to reduce the voltage required to achieve corona discharge. This scheme has the following beneficial behaviours:

- Arc formation is impossible; calibration effort and control system complexity may therefore be reduced.
- The central electrode is not exposed and hence not subject to corrosion by combustion gas, nor to electrical erosion.
- The central electrode is completely covered and the ground “electrode” is, by virtue of the construction, at a low temperature. This avoids any high-load thermal problems which may affect other designs.
- Energy transfer from corona to gas is good, although this may be partially offset by proximity to the insulator and ground.
- The corona may form simultaneously wherever the electric field is high and may be maintained for the duration of the corona event, giving an increased probability of ignition.
- The location of corona formation is controlled by the plug design and known in advance. Extra space around the igniter for corona formation is not required.

Naturally, these benefits must be considered in light of some disadvantages:

- To achieve sufficient electric field, this type of design requires a higher drive voltage than those discussed above. This means that the system has a higher energy requirement which impacts the entire power supply chain.
- Large exposed insulator cross section can lead to high forces on the insulator from motion of combustion gasses. Mechanical design requires care.
- The ignition location is not optimal:

- In the plug of Figure 3.1, corona formation takes place in the plug counterbore region which is retracted from the main combustion chamber. The early flame must propagate out of this region before the main charge can be burned.
- Figure 3.2 [3] shows a scheme designed to reduce this limitation, where the extent of the ground electrode is limited and the corona location is projected as far as possible towards the chamber. Some additional benefit is achieved by the shape of the insulator near the tip. The situation is improved but ignition is still between electrodes and with limited projection from the metal walls of the plug.
- Figure 3.3 [4] shows another scheme to overcome these limits. In this case the ground electrode, which may have various forms, is projected into the combustion chamber. Again, there is some limited improvement but this time at the expense of thermal performance: an electrode which is slight enough to present no impediment to the flame will also be very difficult to keep cool, especially at high load.

Note that an alternative scheme is similar to Figure 3.1 but has the insulator covering the ground electrode and the air gap immediately adjacent to the central electrode [4]. This scheme is less common as it is prone to arcing from the central electrode to other grounded engine parts, reducing its effectiveness.

1.4 Pulse Design Igniters

These designs, such as represented in Figure 4 [5], generally have (but are not required to have) open electrodes exposed to the combustion chamber. To create ignition a pulse at very high voltage is applied to an electrode which ionizes the gas in the combustion chamber, either between a single electrode and the walls of the combustion chamber, or between relatively widely-spaced electrodes. The length of the pulse must be extremely short, in the order of tens of nanoseconds, and is controlled to avoid arc formation.

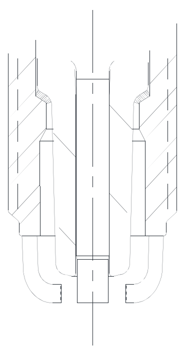


Figure 4: Exemplary Pulse Design Igniter.
Reference [5].

This system is beneficial because:

- Ignition over a large volume is possible, leading to the possibility of near-optimal combustion.

- Calibration effort is reduced due to the inherent resistance to arc formation.
- Avoidance of arc also allows the system to have minimal electrical erosion of the electrodes.
- Energy transfer to the gas is good, leading to the possibility of a highly efficient system.

However, there are some obstacles to adoption:
- To deliver large ignition volumes, a very high voltage pulse is required. With more conventional voltages (20-30kV), the size of the ignition source is greatly restricted (for example, 1.5mm gap between electrodes).
- Delivery of the extremely short pulse required can be very difficult and systems capable of this are technically immature. There may be difficulties in packaging and durability of the system.

2 Optimisation of Streamer Plug Designs

Previous designs favoured by Federal-Mogul have mostly been of the “streamer” type. These plugs have the multiple benefits of excellent ignition performance, relative ease of driving circuit design, and similarity in construction to conventional sparkplugs. This latter advantage is especially important if a product is to successfully transition from the test environment and into the mass market. The advantages to be gained by using spatially extended corona igniters are well known [6, 7, 8], and methods of implementing such systems have been previously developed [9]. Critical to the success of any such system is the ability to manage the ever-increasing thermal loads presented by modern engine developments, and to manage high electrical stresses in order to meet the desire for smaller plug envelopes in future engines.

2.1 Thermal Optimisation

Consider for this discussion the designs of long reach m12 with a flat external gasket seat, as this plug represents the current design most widely adopted in the automotive marketplace. The considerations presented here are applicable to plugs of every different thread size.

Initial designs were coloured heavily by the electrical requirements of the system; specifically the requirement for high dielectric strength and low capacitance of the high-voltage components which translates directly into a higher system efficiency. These designs had the following common features:
- The smallest possible central electrode diameter, allowing the insulator to be thicker and so increasing dielectric strength and reducing capacitance.
- The largest possible insulator diameter, for similar reasons.
- Omitting the lower internal seat of the insulator, which again allows a thicker insulator to be used in the critical region inside the thread body. This may be achieved by:

- Seating the insulator in the larger body of the shell, instead of inside the thread body.
- Alternatively, by using an interference fit between shell and insulator [17].

In addition, alternative insulator materials may be used. Conventional sparkplugs use alumina due to its well-known thermal, electrical and mechanical properties, coupled with its wide application and manufacturability. But other materials are possible in an effort to reduce capacitance, most notably boron nitride, which allows a considerable reduction in capacitance of the plug.

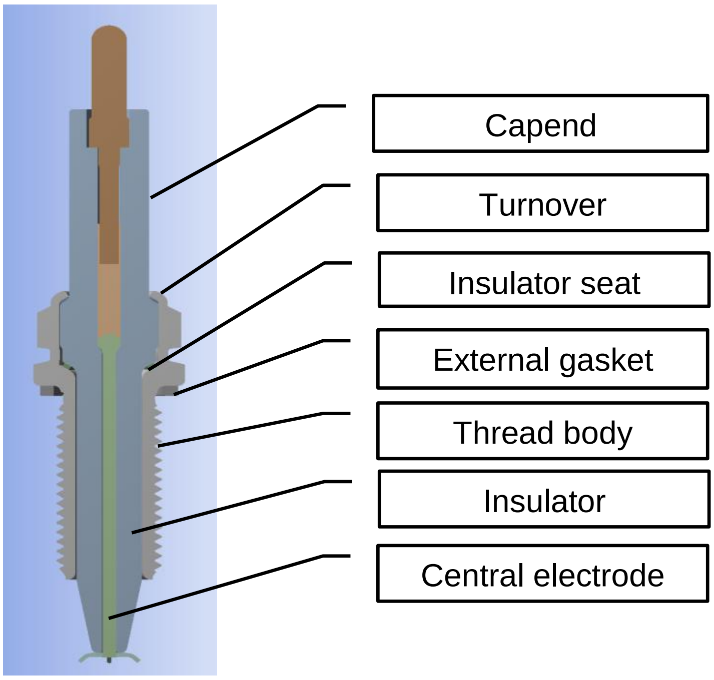


Figure 5: Early Igniter Design
Optimised for Electrical Performance

Figure 5 shows an igniter with these features. This design has a small-diameter central electrode (typically 1-1.5mm diameter) surrounded by alumina insulator (typically 8mm diameter), this electrode extending at this small diameter through the complete threaded portion of the plug. Owing to the small diameter, the electrode is of a single material, usually a nickel-based alloy. Addition of a thermally conductive core, usually a copper alloy, is possible but would result in only a small thermal benefit due to the very limited cross section which can be included. The insulator is seated inside the shell at the location of the larger diameter portion, in order to maintain maximum possible thickness. Portions of the design in the capend region are close to conventional sparkplug practice.

For illustration purposes, a heat load typical of a mass production engine of current design is applied, with a fixed metal temperature and a heat load representing around 100 kW/l, or IMEP of 20-25 bar, for example. This heat load does not represent a specific engine design, but can be used to compare between plugs in a qualitative manner; it has been previously demonstrated that this type of analysis closely follows the changes observed in testing of physical parts. Figure 6 shows the temperature field predicted for a typical conventional sparkplug with this heat load applied.

Here the ground electrode, which has a copper core to assist in thermal control, reaches the highest temperature at around 820°C. The insulator reaches around 810°C and the central electrode, again cooled with a copper core, does not exceed 780°C. As a target for design, an insulator temperature in the range 750-850°C is desirable; this range is cool enough to avoid the possibility of preignition due to hot-spots on the surface, while hot enough to allow burn-off of combustion deposits. The metal electrodes may be safely operated close to 950°C but it is advisable for good durability to keep the electrode temperatures low and certainly under 900°C.

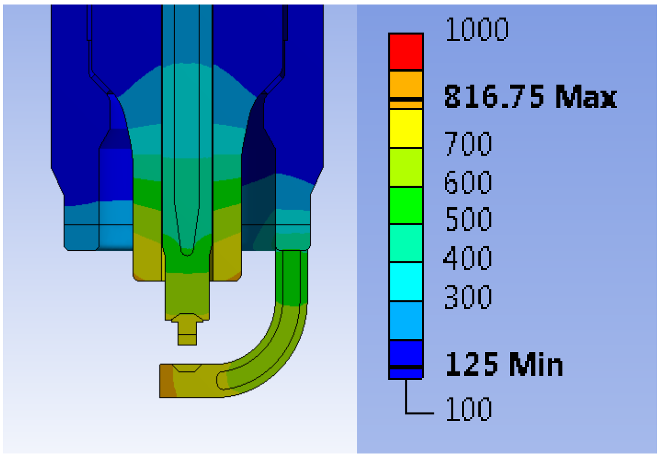


Figure 6: Example Spark Plug Thermal Field [°C]
Representative FEA load applied

Compare these results with the temperature field in Figure 7, representing the igniter design of Figure 5, having the same corenose length as the conventional sparkplug shown above. Temperatures throughout the firing end assembly are far too hot for safe operation: all components are well over 1000°C. Note that, in this analysis, the very high temperatures lead to a disproportionate cooling effect from radiation; at more realistic temperatures the difference between this and cooler designs would be even greater.

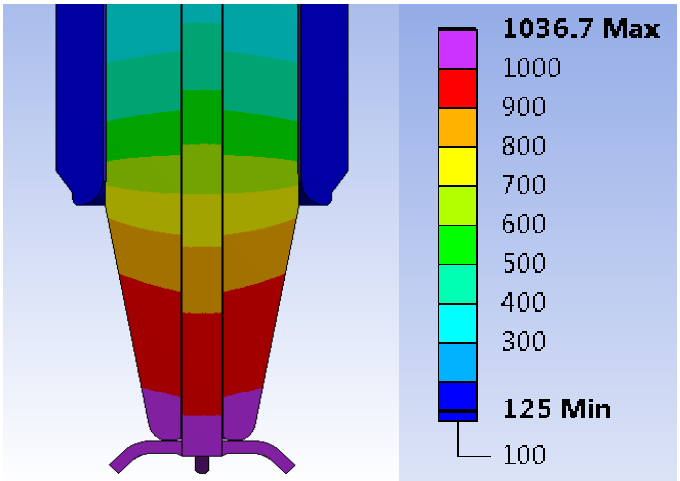


Figure 7: Early Igniter Design: Thermal Behaviour
Temperature [°C]

Although designs of this type were able to operate successfully in an engine, the specific output was limited to around 10-12bar IMEP due to the high operating temperatures at higher load. Steps were taken to cool the plug, for example by filling the gap between insulator and shell with a thermally conductive ceramic-based adhesive [10], but durability of such solutions was marginal.

An obvious first optimisation step is to include a copper core to cool the central electrode and hence star tip and insulator [11]. Due to the very limited amount of copper which can be added to a small diameter electrode, the electrode cross section is increased, even if this has some detrimental effect on parasitic capacitance and dielectric strength. Figure 8 shows how the temperature is affected with the same example FEA loading.

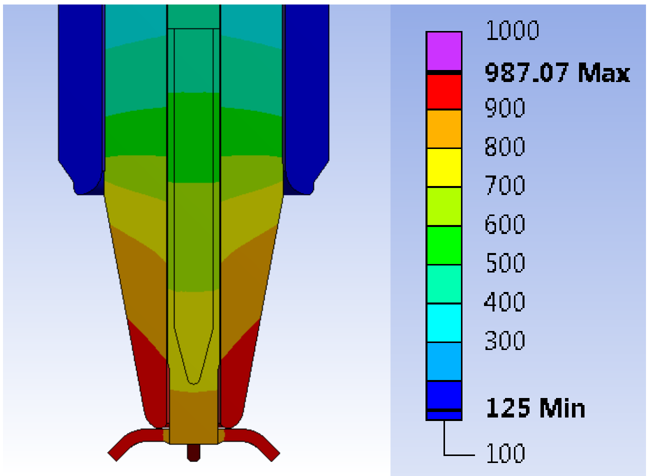


Figure 8: Modified Central Electrode [°C]
Copper-cored nickel alloy (lower portion) and solid copper (upper portion)

In this case it is clear that a very useful reduction in temperatures has resulted: the insulator peak is under 990°C while the star and central electrode fall to 965 and 890°C respectively. This is up to 100°C lower than the previous design and is a big contribution to a design suitable for higher output engines.

It is apparent from Figures 7 and 8 that there is a large temperature differential between the insulator and the shell in the portion of the plug close to the combustion chamber. The high temperature in the insulator in this region hampers design efforts to reduce corenose and electrode temperatures. A number of schemes can be devised to reduce this temperature difference, for example as shown in Figure 9.

In the upper image of Figure 9, the insulator is inserted from the top; an assembly method known as “forward assembly”. The insulator diameter is reduced towards the combustion chamber end in order to provide a seat for the insulator to contact the shell. This provides good thermal contact and leads to a great reduction in insulator temperature in this region. A ceramic insert is placed between the shell and the insulator from below, bonded with a ceramic adhesive or by other suitable method [12]. This insert allows the insulator diameter to be effectively increased in this region and still allows assembly of the plug while helping to control parasitic capacitance. These modifications reduces the insulator to 920°C while the star and central electrode fall to 915°C and 785°C respectively.

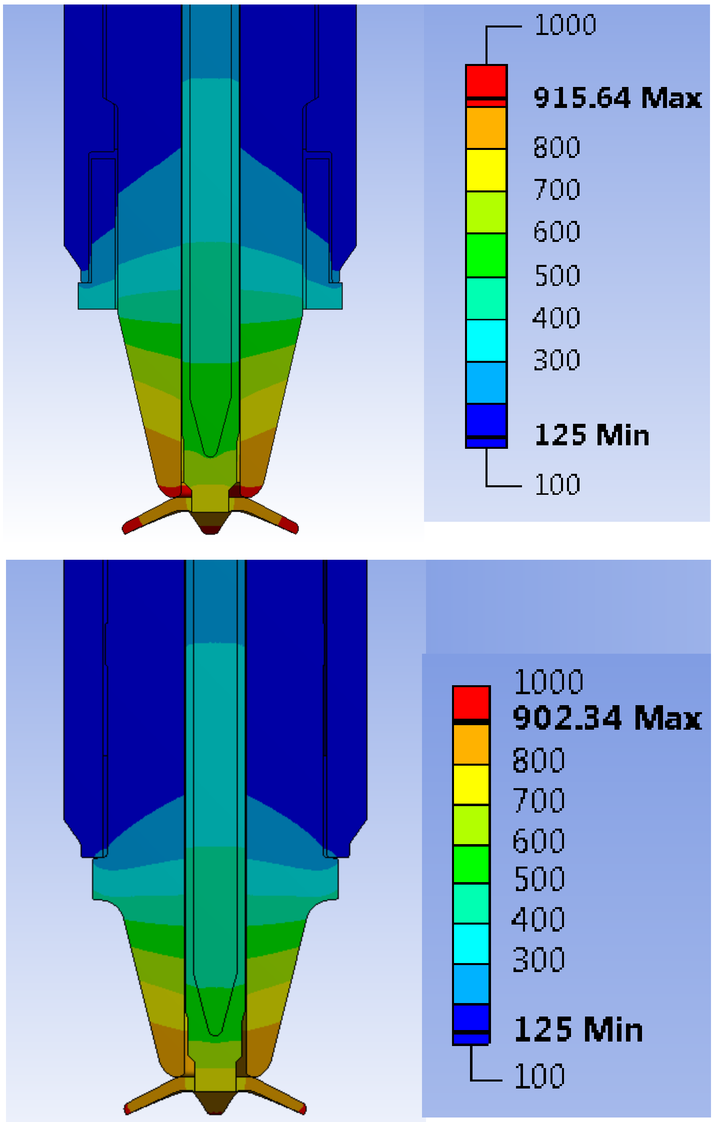


Figure 9: Modified Lower Insulator/Shell Connection [°C]
Upper Image: Forward Assembled with Insert
Lower Image: Reverse Assembled with Braze

Now the lower image of Figure 9 shows a different construction method known as "reverse assembly". In this case the insulator largest diameter is the flange at the base of the corenose which is coplanar with the end of the shell. Here the insulator is inserted into the shell from below and retained in the region just above the flange, typically by an intermediate part such as by brazing the ceramic to the shell [13]. There is no retention of the insulator at the capend which allows for reduced stresses and a simplified assembly. The excellent heat transfer from insulator to shell at the brazed joint, coupled with the fact that there is no reduction in insulator outside diameter at the joint, make this an attractive option. Temperatures in this design fall to 900°C for the insulator, and 900°C and 770°C for the star tip and central electrode respectively.

There are two final contributors to the high temperatures observed in streamer-type corona igniters: the high temperature rise across the thin star tips and the high insulator projection required in early designs.

Modifications to the star tips can give a useful temperature reduction, mostly leading to improved durability rather than safer high-load operation. Most notably changes to the diameter of the central electrode as it connects to the star, profile and material of the base star shape, the addition of thermally conductive star tips where the temperature is highest, and especially use of precious metal tips which have the twin benefits of high thermal conductivity and high resistance to corrosion/erosion, as is well known from conventional sparkplug design.

However, a more powerful solution for reduced temperature may be borrowed directly from conventional sparkplug design: shorter corenose length. Original designs such as that in Figure 5 were not optimal in respect of corona formation location, having a tendency to form corona over the surface of the insulator to the shell. To avoid this undesirable situation, the corenose was made longer than was thermally optimum. Careful development of the electrical design has reduced the need for this longer corenose and allowed this parameter freedom to be reduced, subject to analysis of corona formation in the combustion chamber, as previously described [9] elsewhere.

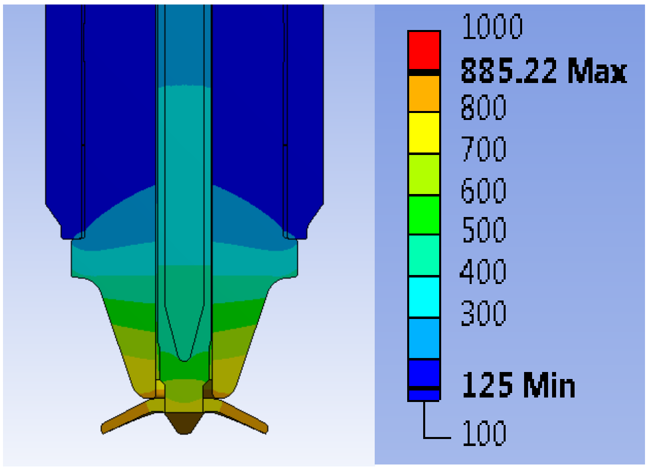


Figure 10: Reduced Corenose Length [°C]

Figure 10 shows the temperatures which may be achieved with this modification. Insulator temperature falls to 815°C with star tip and central electrode predicted at 885°C and 735°C respectively. All temperatures are in the optimal range. Plugs of this design have been shown to run safely at full power in an engine of 30 bar IMEP or more. Figure 11 summarises the optimisations and the results achieved. As mentioned above, design changes can bring all temperatures into the optimal range, but further modifications to star material and geometry can give an additional fall in star tip temperature if this is required to meet durability targets in a particular application.

Table 1: Cumulative Results of Thermal Optimisation

Plug Configuration				Predicted Temperatures [°C]		
Figure	Copper core central electrode	Reverse assembled	Shorter corenose	Insulator	Central Electrode	Star tip
6	Spark plug with copper core electrodes			809	778	817 (GE)
7	No	No	No	1036	1026	1037
8	Yes	No	No	987	890	964
9 upper	Yes	Insert	No	916	786	913
9 lower	Yes	Braze	No	900	770	902
10	Yes	Braze	Yes	813	735	885

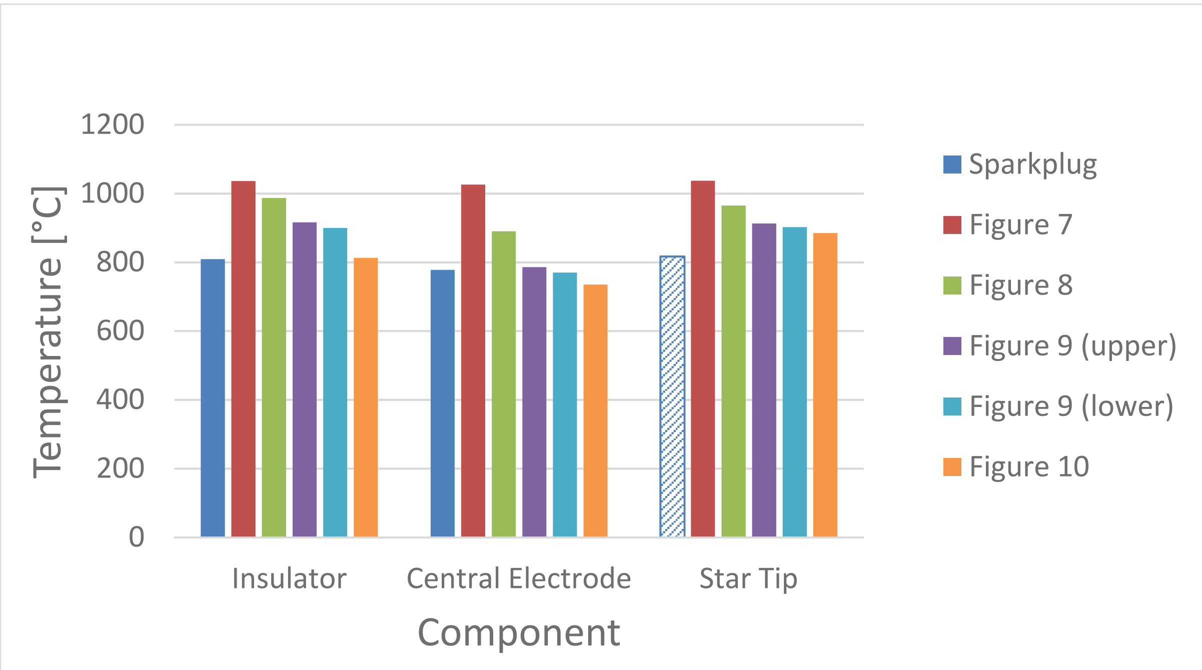


Figure 11: Cumulative Results of Thermal Optimisation
Graphical representation of data in Table 1
Note: sparkplug has ground electrode, not star tip

2.2 Electrical Optimisation

For a streamer igniter design, there are only a few requirements which must be met electrically:

1. For best ignition performance, the ignition location (here, the star tips) should be placed to allow the largest possible corona, depending on the combustion chamber geometry.
2. To ensure that corona is formed in the correct location, the electric field must be maximised in the air at this location i.e. at the igniter star tip in this case. To avoid wasting energy in corona produced at other locations which will not provide an ignition source, the electric field must be significantly higher at the star tip than in air surrounding any other location of the igniter.
3. To reduce the opportunity for corona formation over the insulator surface and subsequent arc formation, the gradient of the field over this surface should be managed.
4. To avoid failure of the igniter, the electric field in the insulator should be low enough that there is no danger of dielectric failure in service, taking into account the thermal and electrical loads encountered.
5. The above requirements should be met while capacitance to ground is minimised.

Each of these requirements is considered in turn below.

2.2.1 Location of Corona Formation

Methods to place the corona source correctly have been previously described [9] and can be summarised by saying that the corona should be located equidistant from all grounded surfaces at time of ignition. This will not be discussed further here.

2.2.2 Electric Field in Air

In order to satisfy the requirement for high local electric field, it is possible to create designs where a high voltage is applied in a small air gap in the igniter, usually in conjunction with a BDI or partially BDI-like design [14]. Corona can form in this small gap and then expand out towards the main combustion charge, either due to continued electrical energy addition, by in-cylinder gas motion, or by the onset of combustion. However, the approach taken here is to use one or more sharp tips to give a high field concentration, directly exposed to the combustion gas. The relationships controlling this high field are well known [15], in general requiring the sharpest possible electrode tip to give the best possible performance.

Figure 12 shows the total electric field at the tip of a streamer igniter design. This FEA result depends on the analysis method used and care must be taken in setting up the problem [16]. In this work a quasi-static analysis is used, with the electrode energised with 1V and the mesh size is fixed in all relevant areas of the model. This makes the results directly comparable between models and between different areas in the same model, and allows results to be directly scaled to give values for any applied voltage. In this case, the peak electric field is 3330 V/m with per volt applied. As the model is quasi-static and therefore linear, this may be restated as a geometrical parameter of the design by normalising for applied voltage, giving a “field concentration factor” of

3330 m^{-1} for this location in this design i.e. for every volt applied, the field here will increase by 3330 V/m.

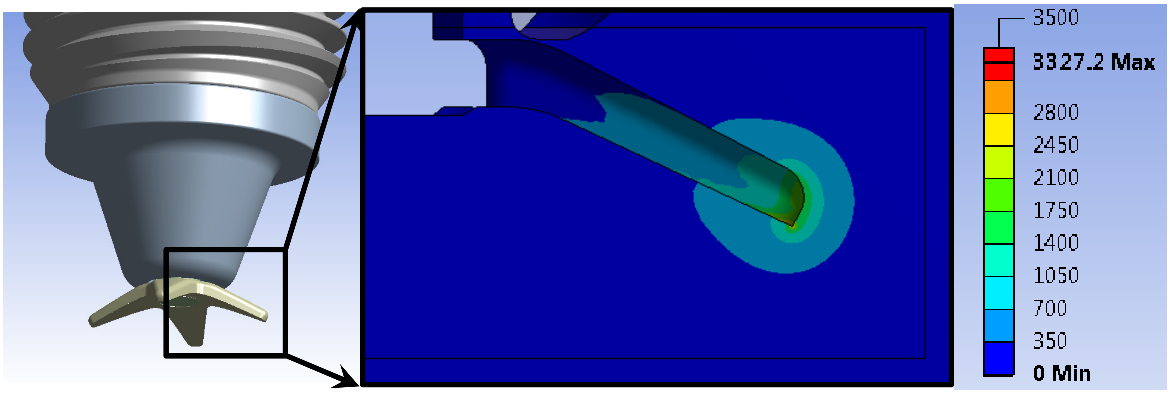


Figure 12: Electric Field Strength at Star Tip [V/m]
1V applied, fixed mesh size

Now in order to avoid having parasitic corona throughout the igniter, we must ensure that corona forms preferentially at the desired location. Corona can only form in ionisable materials which, in the case of corona igniters, means the air gaps in and around the igniter structure. Analysis of these air gaps shows where design changes can help reduce this parasitic corona and improve system efficiency. Figure 13 shows a section through the body of the igniter in cutaway view, cutting through the central electrode, insulator and shell. This igniter shows the features previously described for thermal control, with additional optimisation for brazed assembly: the cavity in this figure is used to help manufacturability of the product and guarantee a hermetic seal in the final assembly.

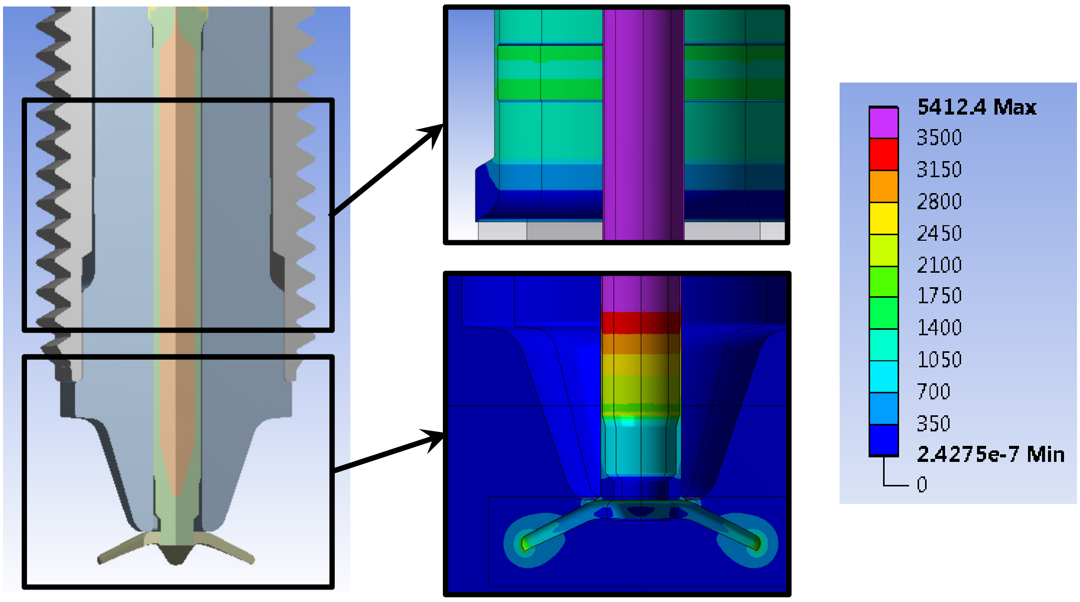


Figure 13: Electric Field Strength in Air Gaps in and around Igniter [V/m]
1V applied, fixed mesh size

Now considering Figure 13, it is desirable that the electric fields calculated in these air gaps are significantly lower than at the star tip as shown in Figure 12. Here we see two areas inside the igniter which need some modification:

- Between the central electrode and the bore of the insulator is a high electric field: up to 5400V/m giving a field concentration factor of 5400 m^{-1}. This is far higher than the field at the star tip (3330 m^{-1}) and is indicative of parasitic corona formation in this area during operation. As corona formation here will be adjacent to the central electrode which is exposed at the star tip, there is no associated danger of arc formation over the insulator surface, but this does represent a significant source of inefficiency as this corona will not contribute to ignition.
- Around the outside of the insulator, the field concentration factor is in the region of 1400 m^{-1} which is much lower than at the star tip and so is unlikely to cause serious problems. However, higher corona energy could still lead to parasitic corona formation in this area, so steps to reduce this would be beneficial.

There are a number of actions which could reduce this undesirably high electric field:

1. The gap could be completely closed by design [17].
    a. By co-moulding of the parts
    b. By interference fit
    c. By bonding the parts together e.g. by chemical bonding
2. The gap could be filled with a non-ionisable material [10].
    a. By an insulator such as epoxy or ceramic adhesive
    b. By a conductive material such as solder, braze or an organic or inorganic filler loaded with conductive material, for example carbon.
3. The surfaces could be coated in a conductive material such that each side of the gap is electrically connected, preventing the formation of a potential difference and hence an electric field [18].

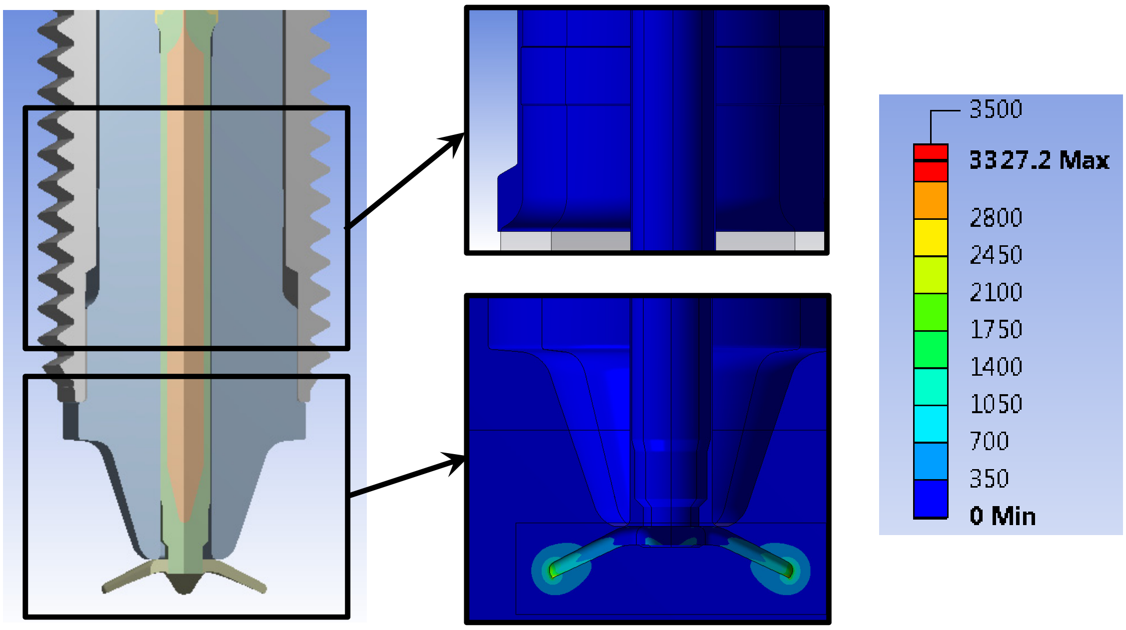


Figure 14: Electric Field Strength with Conductive Coating on Insulator [V/m]
1V applied, fixed mesh size

After considerable FEA and experimental work, it was determined that the most successful solution is to coat the insulator surface with a conductive material. This solution has excellent durability, has almost no effect on the construction process and has no impact on the thermal and mechanical performance after assembly, problems which affect many of the other solutions. The type of coating used in each area does not need to be the same and depends on local conditions [18]: for example the high temperature close to the combustion chamber may require a metal-based coating, while the upper areas of the capend can be treated with a simpler and cheaper carbon-based alternative.

Figure 14 shows the electric field throughout the igniter with the addition of these coatings. Clearly observed is the complete removal of the possible locations for parasitic corona formation within the structure of the igniter. This technique may be applied throughout the igniter assembly: not just in the “spark plug” component, but also in the coil and any connection between the two.

2.2.3 Corona Propagation over Insulator Surface

It is possible for corona to break down into an arc between the high voltage electrode and the grounded engine structure, which leads to all the energy being shunted into a single path, causing a large drop in corona volume and commensurate fall in ignitability performance. This is especially likely over the surface of the insulator where the field required for propagation is lower [19] and may be further reduced by combustion deposits or fuel wetting on the insulator. Ideally this would be achieved by making the field concentration factor very low in all locations except at the star tip. Figure 14 showed how it was possible to reduce electric field in the air gaps inside the igniter to almost zero. However, this method clearly cannot be applied to the corenose of the insulator where a high electrical insulation between central electrode and ground is required. Figure 15 shows the electric field specifically at the root of the corenose, at its interface with the shell, showing (at top) a field concentration factor of around 1530 m^{-1} in the case where the part is perfectly manufactured, rising to 2440 m^{-1} when there is a gap of just 25µm between the flange and the end of the shell (at bottom);

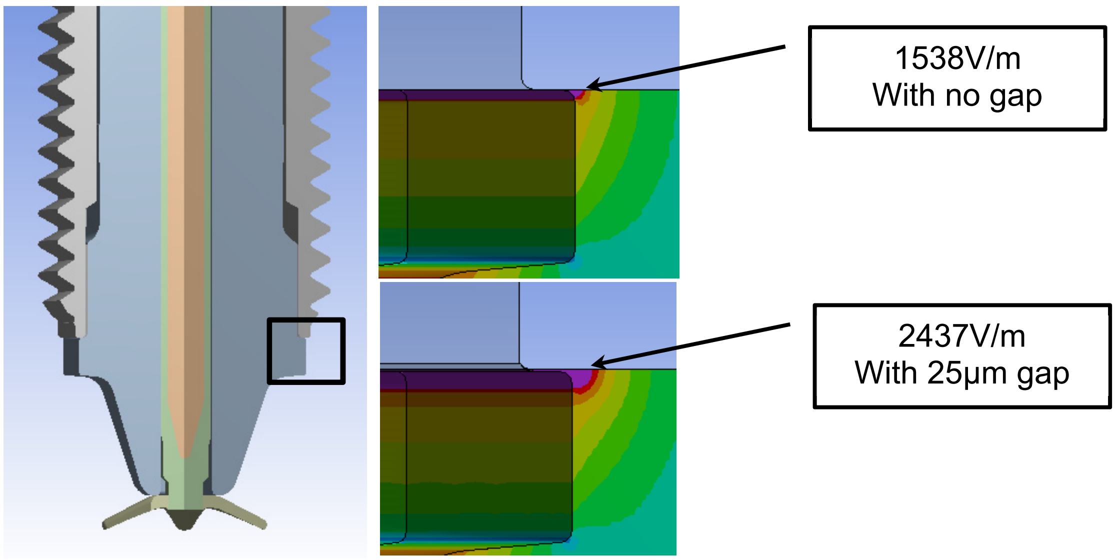


Figure 15: Electric Field at Insulator Corenose Root [V/m]
1V applied, fixed mesh size

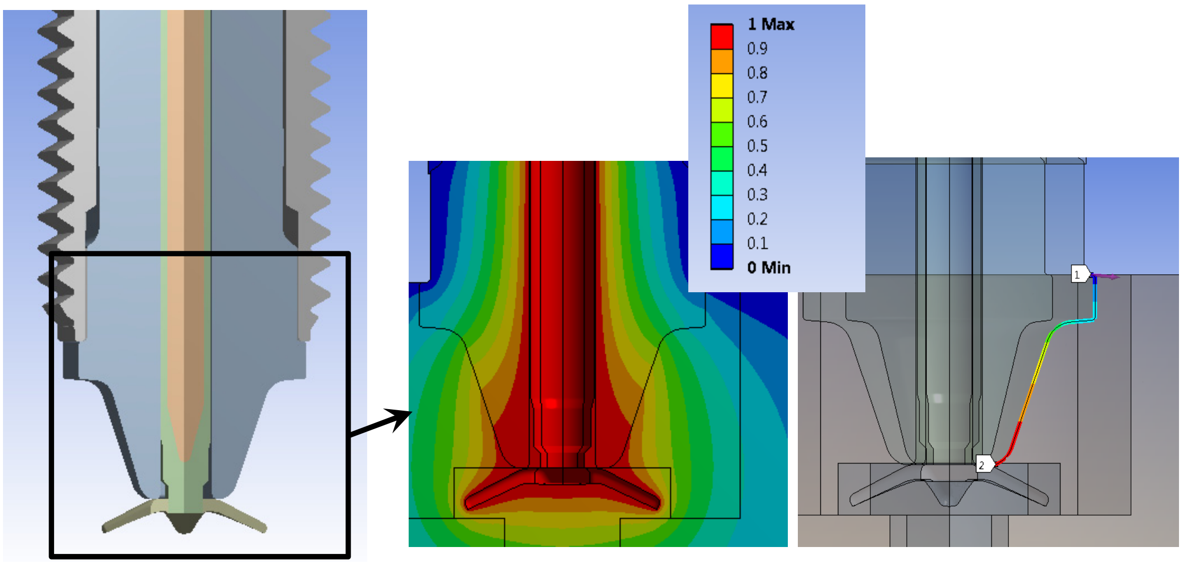


Figure 16: Voltage at Insulator Corenose Region [V]
1V applied, fixed mesh size

compare these values to 3330 m^{-1} at the star tip and it is clear that some corona formation might be expected here at higher voltages in real igniters.

Corona formation in the air around the igniter is driven by the total electric field, as discussed above. However, once this corona has formed, its propagation over the insulator surfaces is controlled by electric field in the direction of the surface, which requires a special method of analysis. Figure 16 shows a detail view of the corenose region of a corona igniter previously discussed in Figure 14. In this figure the possible path for arc formation over the insulator is identified (between “1” and “2” in the right image) and the voltage along this path plotted. If the electric field is evaluated in the direction of this surface, it is possible to evaluate the propagation of corona [9].

Consider the situation at the interface between shell and insulator at location “1” when a positive voltage is applied at the central electrode. Once a high electric field has ionised the surrounding air, the positive ions are immediately attracted to the grounded shell, leaving a cloud with negative charge. This cloud is attracted to the positive central electrode but cannot move directly due to the interposed insulator; it therefore propagates over the surface of the insulator so long as it is moving in the direction of increasing voltage, that is: positive electric field. If the corona can propagate all the way to the central electrode, an undesirable arc will form. To avoid this, the shape of the insulator is carefully designed to ensure that the gradient of electric field measured in the direction of the surface, is not conducive to this arc formation [9]. Of course, this does not prevent arc formation in the free air of the combustion chamber; this must be addressed, as in section 2.2.1, by proper placement and geometry of the igniter.

In Figure 17 we see an evaluation of the electric field over the surface of the insulator between “1” and “2” as defined above, starting from the shell and finishing at the central electrode. This figure shows how the negatively charged corona formed as described above is unable to propagate over the surface of the insulator due to the reversal of electric field created by the flange at Y=0.1mm. The flange has a number of beneficial effects:

- It increases the distance over the corenose, reducing the chance of arc formation and fouling. In this design, around 1.5mm is added to the distance over the surface.
- It creates a field reversal as shown in Figure 17 which prevents propagation of corona over the surface and prevents arc formation. The flange need not cover the end of the shell; the angle and length of the sides of the flange is important but the extent need only be small. Here it is less than 0.4mm and covers less than half of the shell firing face, but performance is excellent.
- There is a secondary reduction in field at Y=1.5mm which is often enough to arrest corona propagation (depending on applied voltage), giving increased arc protection.
- It provides a mechanical limit for the insulator during "reverse assembly" which sets the geometry of the firing end accurately.

These benefits allow a shorter corenose to be used which allows greater freedom in locating the corona inception point, increased ability to maintain compression ratio by keeping the igniter away from the piston, and allows operation at a higher specific load than would otherwise be possible due to improved thermal management.

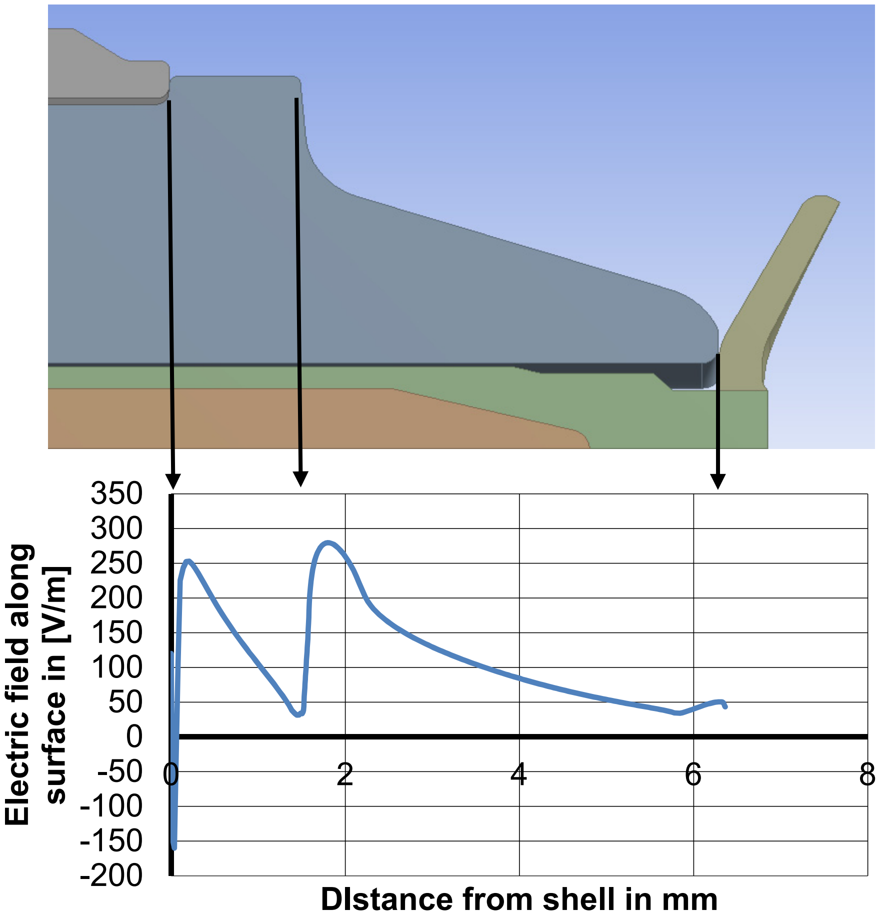


Figure 17: Electric Field over Insulator Corenose Surface [V/m]
1V applied, fixed mesh size

2.2.4 Electrical Safety of Insulator

Development of an insulator design for a corona igniter is based heavily on extensive experience when using similar materials in sparkplug applications. The dielectric strength of alumina insulators depends on a number of factors:

- Composition and structure of the insulator material.
- The average electric field; that is, the voltage across the material divided by the thickness of the material.
- The presence of any local stress-raisers which lead to locally high electric fields in or adjacent to the insulator.
- Material thickness; since ceramic materials always contain defects in their structure and failure may be described statistically based on the number and distribution of such failures in the sample. The result is that the strength per mm decreases as thickness increases, even if the actual strength is still increasing.
- High temperature reduces ceramic strength as it approaches the softening temperature of the glass phase in the alumina. Careful composition of the material reduces this but it cannot be eliminated.

For a typical sparkplug geometry, these factors result in a dielectric breakdown strength of around 16kV/mm for a standard production alumina ceramic under operational conditions. Using this as a limit for corona igniter design has proved reasonable in testing performed internally, since the frequency and pattern of application of the high voltage has not been shown to alter this result significantly.

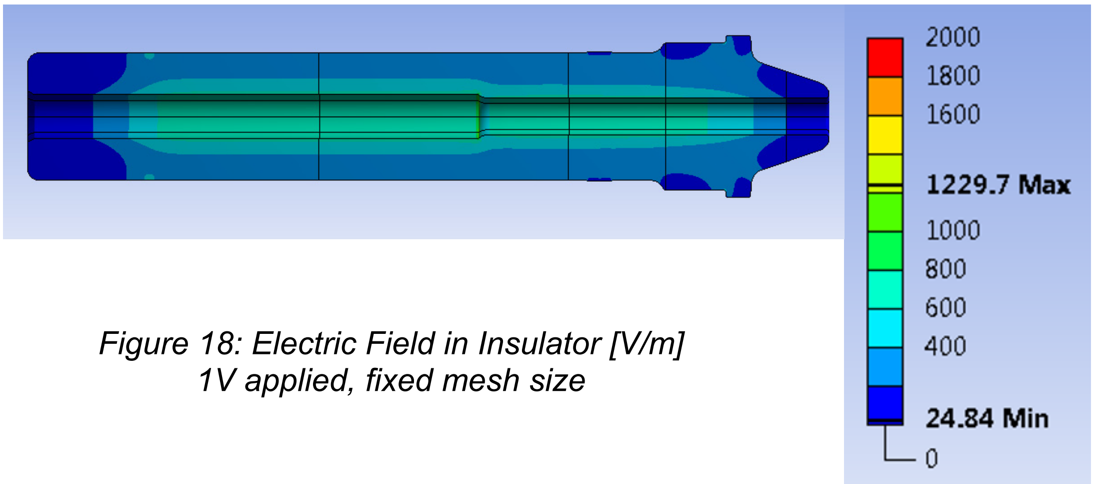


Figure 18: Electric Field in Insulator [V/m]
1V applied, fixed mesh size

Figure 18 shows how electric field in the insulator varies with 1V applied. The average field in the insulator is 386V/m meaning the bulk breakdown strength would be around 84kVpp. Local peak values close to the insulator bore are 480V/m, which is not high enough to significantly reduce this estimate. A local maximum of 1230V/m occurs at the central electrode head and this reduces the estimate slightly to around 75kVpp. No insulator failures have been noted in this region with igniters of this design, indicating that the analysis is valid and allowing the calculation of a worst-case safety margin of around 15-25% over lifetime and operating range, based on known existing engine operating maps

2.2.5 Control of Parasitic Capacitance

Many of the steps taken above, while necessary, lead to a higher parasitic capacitance and a reduction in electrical performance of the system. The initial design of Figure 7 had a firing-end capacitance of around 7pF when manufactured in boron nitride. However, this material had mechanical difficulties as well as an ability to absorb moisture, making it unsuitable for use where the target engine must perform cold starting. In conjunction with improved manufacturability, this led the adoption of alumina as the material of choice; this change caused the capacitance to increase to around 17pF.

Features which increased capacitance during the design optimisation include:

- Use of alumina ceramic.
- Adoption of a thicker copper-cored central electrode.
- Use of a lower internal seat in the shell.
- Conductive coatings for control of parasitic corona formation.

But these increases were offset by additional design changes:

- Larger shell bore allowing larger insulator diameter.
- Subsequent removal of the internal shell seat with the adoption of "reverse assembly" construction.
- Reducing the length of the capend portion to cut down the amount of high-permittivity alumina in the design.

Cumulatively these changes result in an increase from 17pF to 19pF total capacitance of the firing end. Now the total capacitance connected to the high voltage tip is the parameter which controls the system behaviour. This total capacitance includes not only the firing end but also the output side of the coil and any connection between the two. In designs suitable for installation in automotive engines, the total parasitic capacitance is in the region of 35pF from all sources. In this context, an increase of around 2pF represents only 6% which is an acceptable increase in view of the improved mechanical and thermal robustness which can be achieved.

3 Igniter Downsizing

As previously mentioned, there is a desire in the marketplace for plugs of ever-smaller dimensions in order to facilitate the implementation of direct injection strategies, more complex valvetrains, and to help facilitate the cooling required for increasd specific output. While the designs above may easily be expanded to make larger plugs with 14mm or 18mm thread bodies, reducing the size presents different challenges:

- Thermal management becomes difficult as the projection into the chamber must be maintained for good ignition, making the corenose long and thin. In conjunction with the limited diameter central electrode this can make the plugs run hotter than optimal.
- Smaller insulator diameter leads to reduced dielectric strength and increased loss due to parasitic capacitance.
- The connection between the firing end and the rest of the igniter assembly becomes difficult as there is a very high electric field across the upper end of the insulator which increases as diameter decreases.

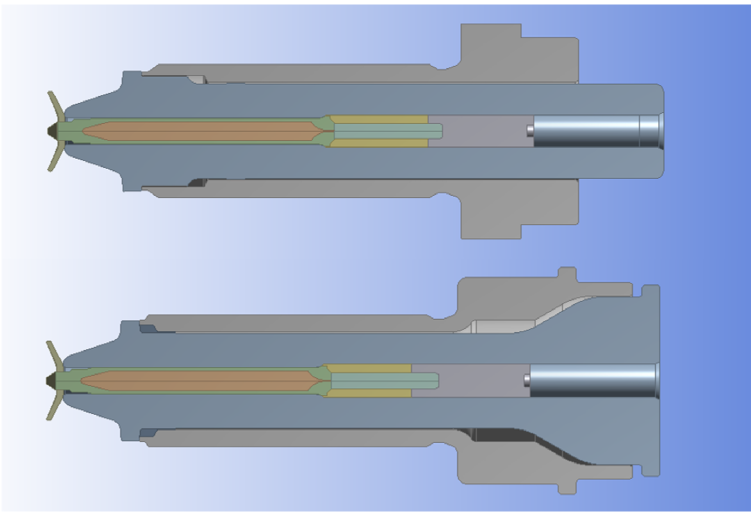


Figure 19: m12 "Barbell" Design for Size Reduction

Consider a possible solution to some of these problems, implemented in a 12mm thread body, and shown in Figure 19. The upper image shows the optimised "reverse assembly" part as previously discussed (previously in Figure 10), while the lower image shows an example of the "barbell" design developed specifically for small diameter variants [20]. This has the following features:

- Insulator corenose shape is identical giving similar performance, including ignitability.
- Insulator diameter is slightly reduced under the corenose flange leading to a possible increase in capacitance. This is offset by the larger diameter insulator at the "capend" region.
- Assembly is still similar to "reverse assembly" in that the insulator is held in a single region close to the firing end of the shell, affixed as before by a hermetic seal such as solder, brazing or similar.
- The shell is formed around the insulator by a specially-developed process, designed to install the insulator into the shell without mechanical stress.
- The "capend" of the insulator has a large diameter, both to reduce parasitic capacitance and to increase the electrical strength of this connection.
- In this case, the central electrode is unchanged between designs, giving near-identical thermal performance.

This design allows the possibility of reduced diameter, either with the same central electrode for similar thermal performance, or with a specially-developed smaller diameter central electrode to give improved electrical performance. Figure 20 shows an example of such a design, both the computer model and the physical parts, with Table 2 showing the performance which can be achieved, taking the optimised plug of Figure 10 as a baseline.

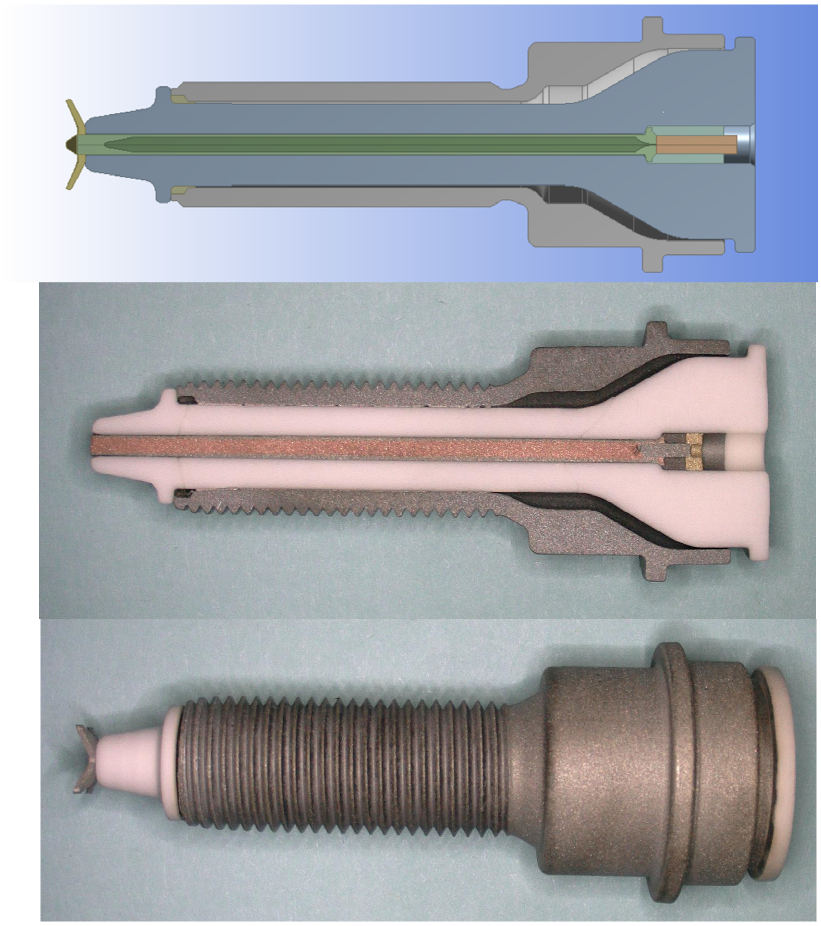


Figure 20: m10 "Barbell" Design for Size Reduction

Table 2: Thermal and Electrical Performance of Downsized Igniter

Design	Star temperature	Insulator temperature	Demand voltage	Dielectric strength (insulator)	Dielectric strength (connection)	Parasitic capacitance
m12 reverse assembly	100%	100%	100%	100%	100%	100%
m12 barbell	100%	100%	100%	100%	394%	110%
m10 barbell (cool)	+11°C ≈102%	+51°C ≈107%	100%	83%	394%	133%
m10 barbell (hot)	+26°C ≈104%	-1°C ≈100%	100%	100%	394%	96%

Notes:

- The "cool" m10 barbell has similar central electrode to optimised m12 design. This controls the central electrode and star temperature at the expense of dielectric strength and capacitance. The thinner insulator corenose section leads to higher local temperature. This may be addressed in electrode design.

- The “hot” m10 barbell is as shown in Figure 20. A small diameter electrode improves electrical parameters, while a specially-developed copper core process offsets the temperature increase. Insulator temperature is additionally controlled by details of the electrode design.

Analytical and experimental work has shown that corona igniter plugs having a 10mm thread body may be manufactured and operated with only a very small penalty in performance. Specially-developed components and assembly methods allow the designer to overcome the potential shortcomings of small diameter igniters in order to achieve electrical behaviour equal or superior to larger diameter plugs, and control the thermal changes to give equivalent temperatures in most locations and only a very modest rise in electrode tip temperature. This work shows the feasibility of downsizing the igniter into a 10mm package.

4 Alternative Solution: BDI

Previous work above has concentrated on the streamer design igniter as this offers excellent ignitability with good system efficiency. As described in section 1 above, BDI plugs offer reduced calibration complexity, elimination of electrode wear, improved thermal management and a relaxed requirement for space envelope in the combustion chamber. This must be offset against a reduction in ignitability (compared to streamer plugs) and a higher power requirement. So the BDI designs discussed above have some potential benefits, provided the efficiency and ignitability is sufficient for engine operation.

The strategy employed to address these problems is three-fold:

1. Expose the insulator corenose as much as possible to the combustion chamber gas to place the insulator surface at a good location for combustion initiation.
2. Deliberately introduce a region of high electric field outside the insulator in order to allow corona inception at an acceptable applied voltage level.
3. Manage the electric field on the insulator surface to ensure that this corona can propagate over the insulator and into the combustion chamber to give best ignitability.

4.1 Electrical Design Process

4.1.1 Expose Corenose to Combustion Gas

Section 1 shows BDI igniters of typical design which have an insulator surrounded by an annular gap and then a grounded surface, allowing the formation of corona in the annular gap. The corona pattern typically generated fills the annular gap with corona but there is little or no projection into the cylinder. Designs have been proposed [3, 4] to improve this but with limited application. Now a design of Figure 21 might provide enhanced ignitability if the surface of the insulator could be covered in corona.

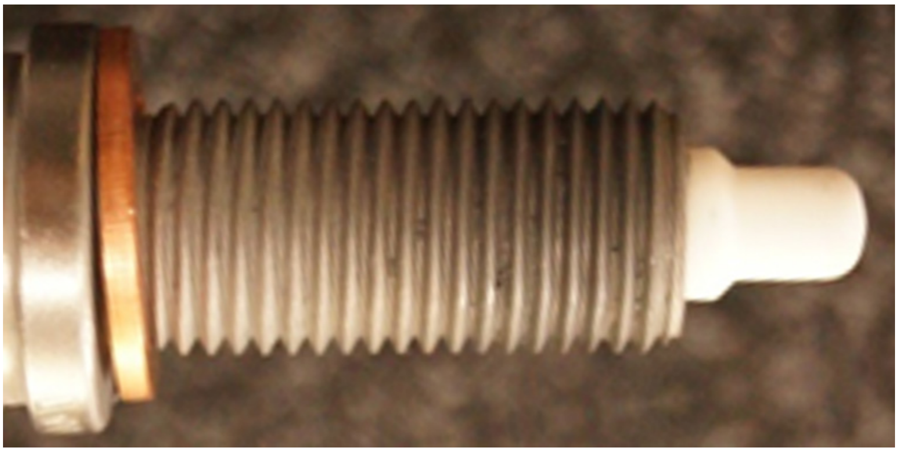


Figure 21: BDI Igniter with Exposed Insulator

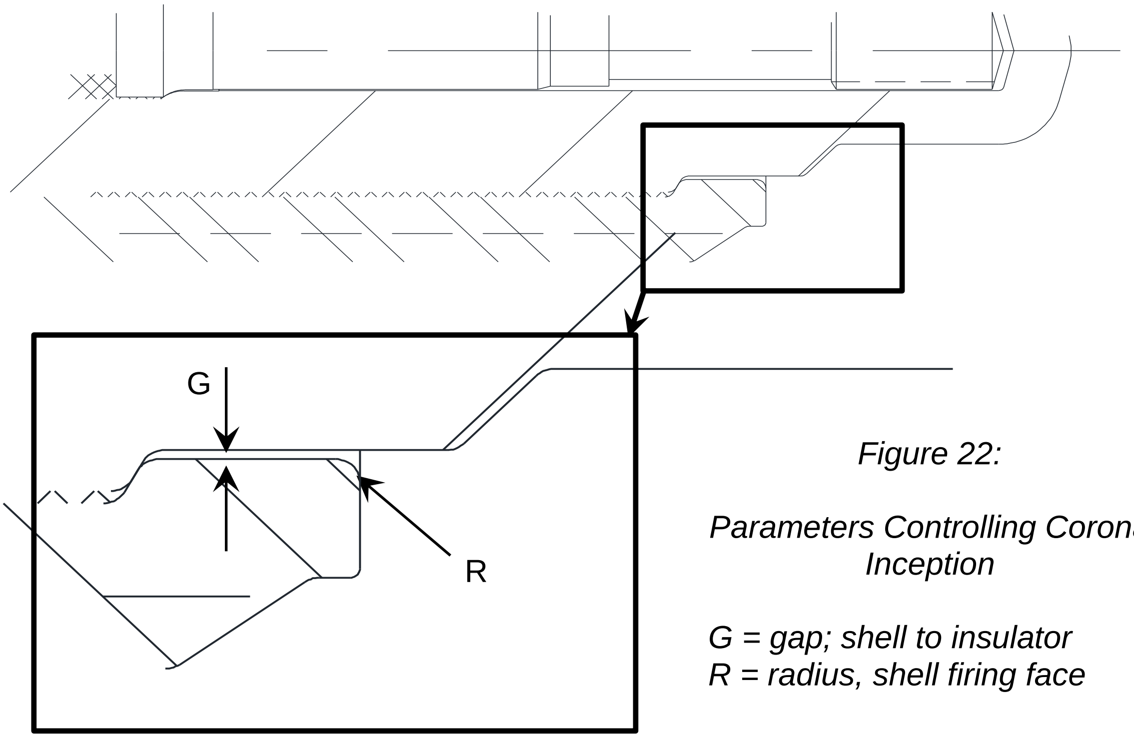


Figure 22:

Parameters Controlling Corona Inception

G = gap; shell to insulator
R = radius, shell firing face

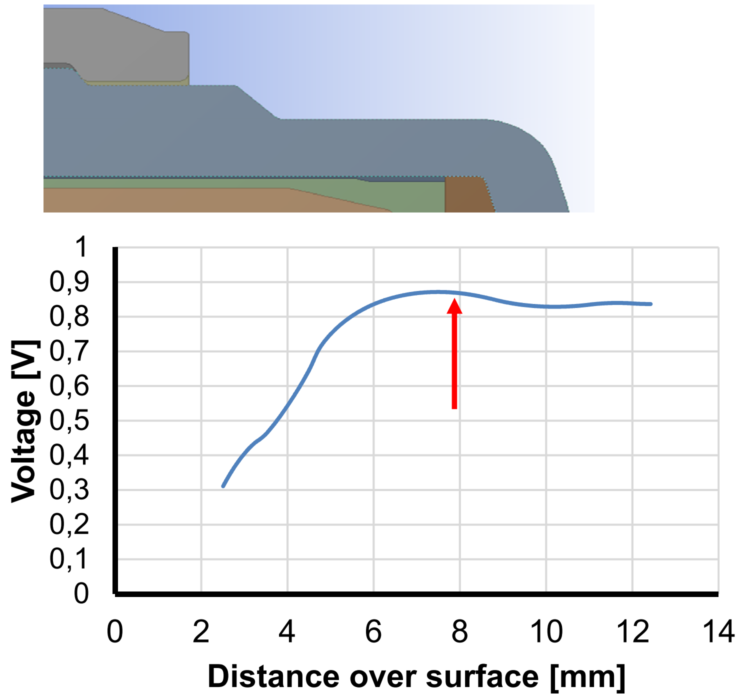
4.1.2 Corona Inception Voltage Control

Steps were taken while designing the streamer plug to prevent the formation of corona except at the tip: reduction of gaps, use of conductive materials, adding features to create a field-reversal to arrest corona propagation. Now the knowledge of those steps allows us to design a BDI plug where corona is deliberately encouraged to occur at a known location and at a known applied voltage. Consider a region around the insulator, where it emerged from the firing face of the shell, as shown in Figure 22. A small gap at G is deliberately created between insulator and shell, and is left open to the combustion chamber at R [21]. The voltage which must be applied in order to create corona may be completely controlled by the geometry in this region; inner and outer diameters of the insulator, the size of the gap G and the radius R of the fillet at the end of the shell. These parameters may be solved analytically or by FEA in order to achieve corona formation in the desired voltage range, while keeping within the tolerances possible for mass production.

4.1.3 Propagation of Corona over Insulator Surface

Methods for analysis of this propagation have been previously described [9] and applied is Section 2.2.3 above. However, the previous target was to prevent the formation of an arc discharge by preventing or interrupting propagation; here the aim is to promote this propagation. In order to achieve this goal we must ensure that the electric field over the surface of the insulator has the same direction at all locations and is of sufficient magnitude to encourage this propagation. Practically, it may be recognised that this means we will observe a steadily rising voltage over the insulator from root to tip. Figure 23 shows the analysis for the plug of Figure 21 and the result of physical testing. It can be seen that the voltage does not rise from tip to root (with the voltage very close the shell omitted due to high local electric field) as there is a reversal at the arrowed section, and the photograph shows that the corona does not propagate beyond this point. Note that the horizontal graph axis is distance over the surface and therefore is longer than the actual projection of the plug into the chamber.

Addition of sufficient corona energy will eventually allow corona to reach the tip due to the effect of the presence of conductive corona on the surface which changes the shape of the electric field. However, it would be desirable to change the shape of the insulator to remove this restriction and allow improved propagation even at lower energy.



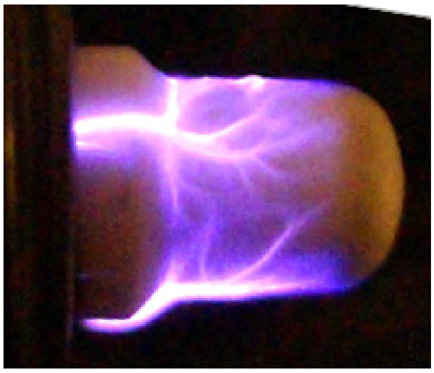


Figure 23:

Corona Propagation With Un-Optimised Projected BDI Design

It has been found that an expression may be derived which predicts if the corona will propagate to the tip of the igniter, based on the length and diameter of the insulator and central electrode, and on the parameters “G” and “R” from Figure 22 above. In addition, in cases where corona will not propagate to the tip, the distance of propagation may be predicted based on a separate expression [22]. This gives two possible solutions for this problem:

1. Plugs with a low aspect ratio of the insulator, that is corenose length divided by corenose root diameter, are more likely to have good propagation. This allows for the solution where a “skirt” is added to extend the shell into the combustion chamber. This allows the effective corenose length, and hence aspect ratio, to be reduced and allow corona propagation to the tip without changing the location of the ignition. The length of skirt required may be calculated using the equations in reference [22].
2. In the case where this is not practical, it is possible to modify the insulator thickness, starting at a location defined by a predictive expression [22], so that the insulator becomes thinner towards the tip. This modifies the shape of the electric field in the desired manner.

Of course, one or both of these methods may be applied to the same design, since each requires different compromises: the first solution reduces the area of corona available to igniter the mixture, and may have high temperatures in the skirt of the shell; the second solution results in a reduction of insulator thickness at the tip and corresponding fall in dielectric strength in this area. Figure 24 shows examples of each of these solutions, side by side with the original un-optimised design for reference. Notice that the central image shows an igniter or BDI design but “reverse assembly” construction. This change is not material to the design of the plug for corona propagation, provided that the correct diameters are used in the evaluation.

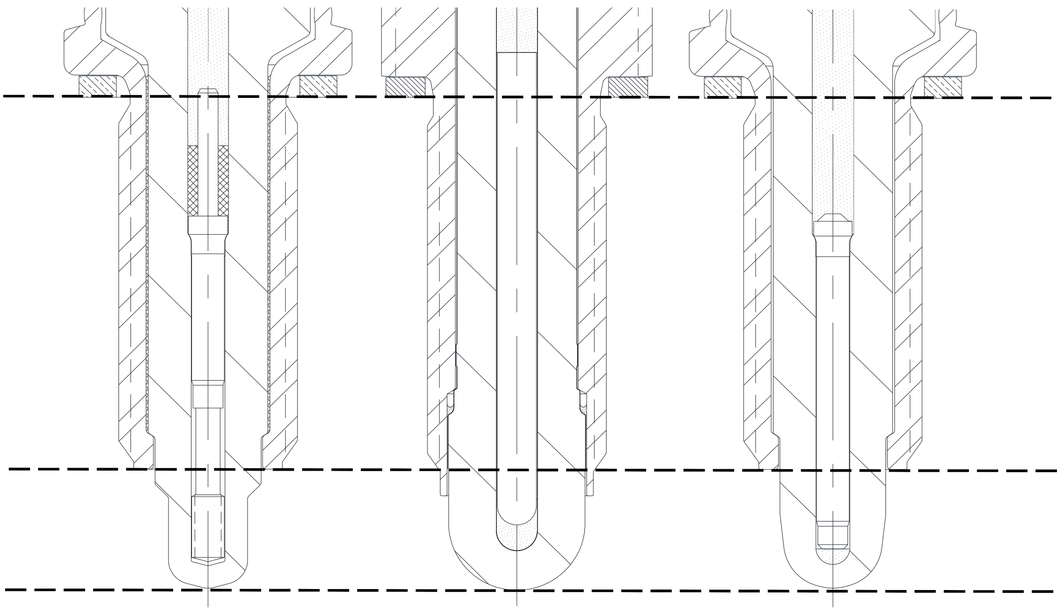
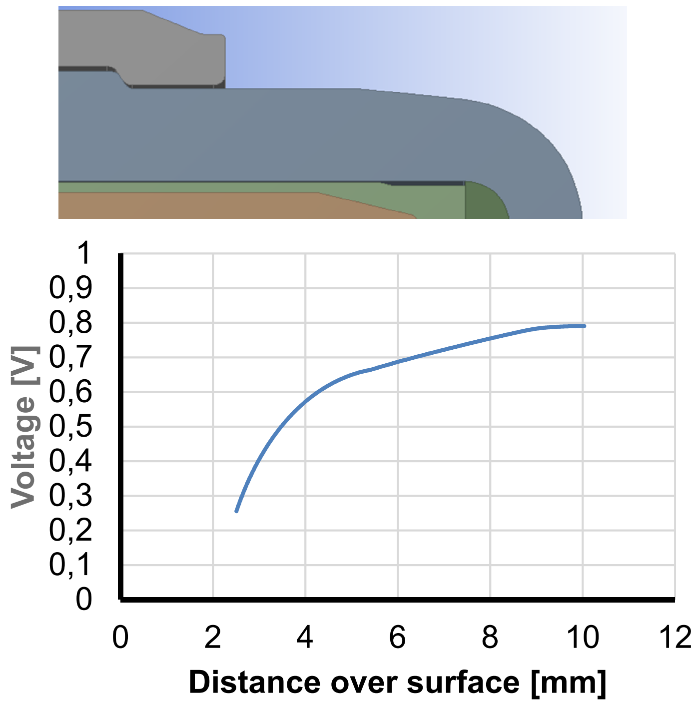


Figure 24: Optimised Projected BDI Designs

Left: un-optimised
Centre: with shell skirt
Right: with reduce insulator thickness

The solution of adding a skirt to the plug shell is trivial and is common practice in sparkplug design. The development here is the ability to know the length required and the application of this technology to the corona igniter, not for thermal or vibration control (as in conventional sparkplugs) but in order to modify the electric field. Most interesting is the solution with a reduction in insulator thickness towards the tip, and the results of such an optimisation is shown in Figure 25. With the same applied voltage it is possible to form more corona and for the corona to propagate further into the combustion chamber. This design would be expected to provide a superior ignition source when compared to earlier designs.



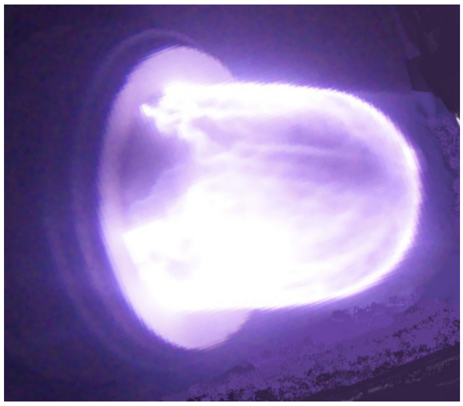


Figure 25:

Corona Propagation With Optimised Projected BDI Design

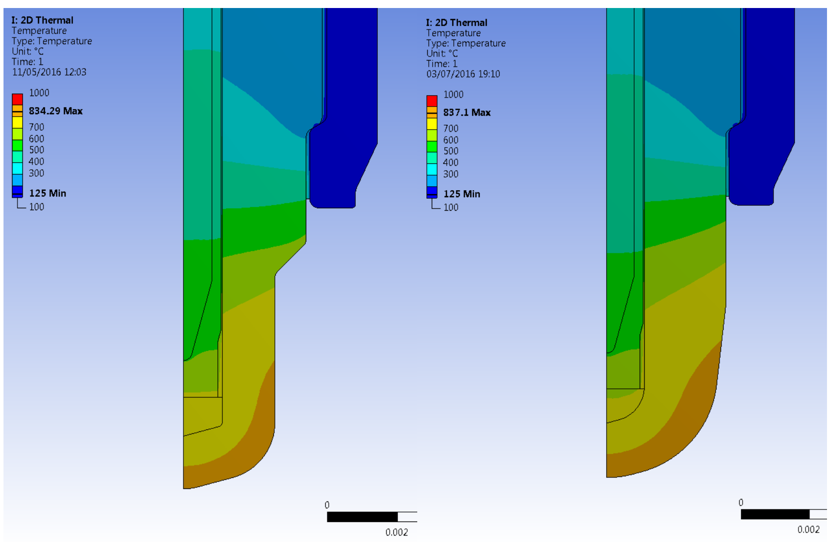


Figure 26: Thermal Performance of BDI Igniters Temperature [°C]

4.2 Thermal Verification

Applying the same thermal loads as those used in Section 2.1 above, we may evaluate the thermal performance of these BDI designs. Previous streamer designs had a maximum temperature on the star tip of around 890°C and an insulator temperature around 815°C, and around 900°C for both in the longer corenose length version. The thermal analysis of Figure 26 shows that the maximum temperature of the BDI plug is around 840°C, well within the safe range for operation despite this igniter having the longer corenose length. This longer length is desirable because the corona will not propagate away from the igniter and through the combustion chamber; increased projection allows the best possible ignition source in this case as there are no concerns about arcing to the piston crown.

4.3 Combustion Results

Igniters of streamer and optimised BDI design were tested in a suitable target engine, against conventional sparkplugs. The engine specifications are typical of a mass-market production engine for automotive use: in-line 4-cylinder, 2 litre displacement, direct injected, turbocharged and with variable valve timing. The engine was operated at a range of speed and load points. For corona igniters, both streamer and BDI, the duration and applied voltage was also varied. In this work the voltage indicated is applied to the drive circuit, not to the igniter directly, and is a proxy for power delivered.

Results from a typical part-load condition, 2000rpm and 9 bar BMEP, are shown in Figure 27 below. It can be seen here that all the optimised BDI igniters perform better than the sparkplugs, showing some additional improvement with increasing voltage. There is a minor sensitivity to corona duration over the limited range tested here. Streamer igniters perform better again than the BDI plugs, showing a strong sensitivity to applied voltage and lesser, but significant, sensitivity to duration.

Results from a typical wide open throttle condition, 4000rpm and WOT, are shown in Figure 28 below. Some relevant points from this graph are:

- Early prototype BDI parts were voltage-limited. Dashed lines in BDI data represent expected performance.
- Both streamer and BDI plugs may be expected perform better than spark plugs if the applied voltage is sufficiently high.
- Best absolute performance is achieved with streamer plugs. However, the falling performance with increasing voltage observed in the streamer plug at 60V applied and 500us corona duration is due to the onset or arc formation at this condition; ignition timing of around 3°BTDC means that the piston is very close to the igniter. Increasing voltage recovers this performance due to operation of the “IOS” system [23]. At shorter corona duration there is insufficient time for arc formation and performance is optimal, shown in the data from streamer plugs operated with 200us corona duration. This is an indication of the performance sensitivity of the streamer plugs at certain operating points and the requirement for careful calibration and suitable measures in place to mitigate these effects.

- Operation of the BDI plugs is not affected by arc formation. This leads to a simpler calibration task and more predictable characteristics in operation.

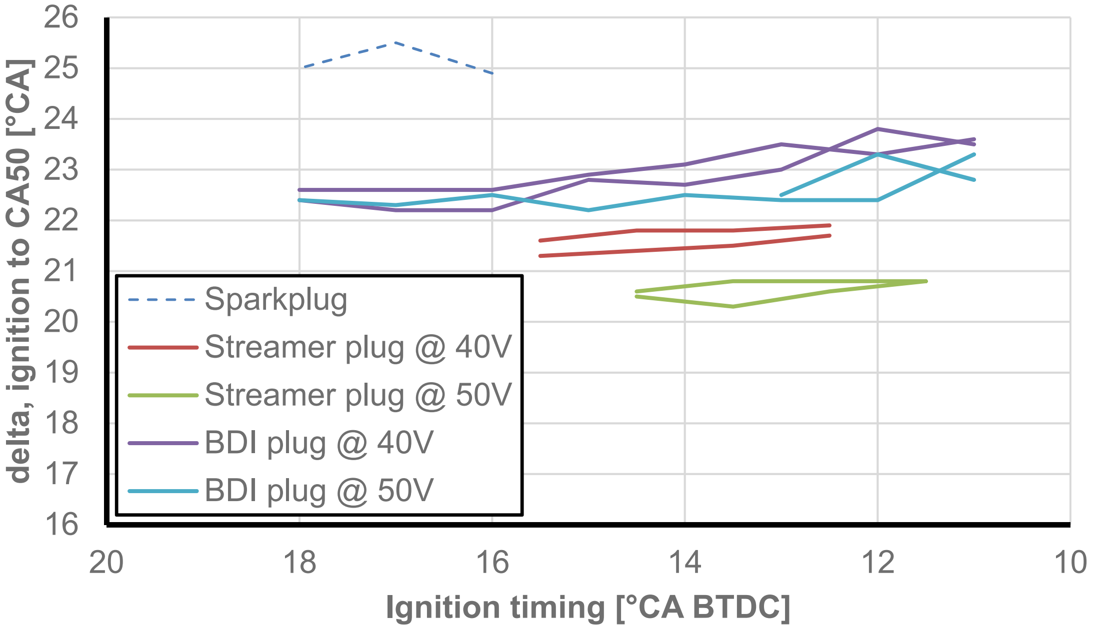


Figure 27: Ignition Performance of all Ignition Sources 2000rpm, 9bar BMEP

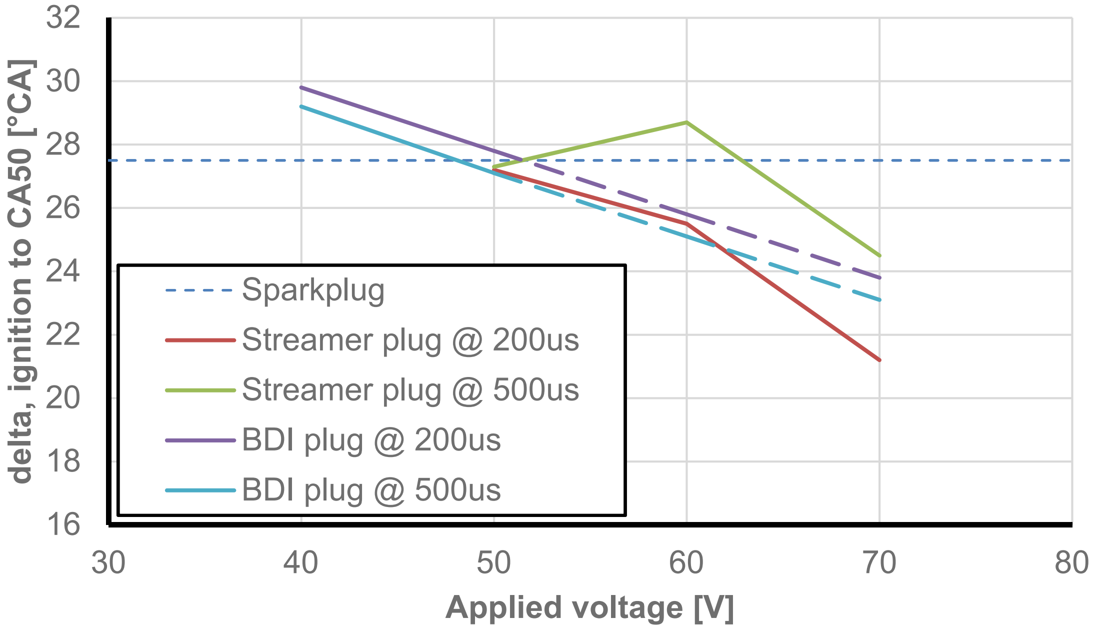


Figure 28: Ignition Performance of all Ignition Sources 4000rpm, WOT

5 Summary and Conclusions

It has been shown how corona igniters of a “streamer” design offer the best available ignition source from a system of this type, and how the firing end of these igniters may be thermally optimised to allow their reliable use in engines with IMEP up to 30 bar and beyond. This has been achieved at the expense of a very minor decrease in system efficiency, in the order of 6%, which is easily offset by material and design changes elsewhere in the system.

It has further been shown that it is possible to reduce the physical size envelope, from the existing 12mm thread in use today, down to a 10mm thread package with minimal impact on electrical performance and a very modest 4% increase in maximum electrode temperature.

An alternative solution is presented which has the potential to provide the following benefits:

- To extend igniter endurance by removing the exposed electrodes.
- To allow operation in engines of still higher specific output by improved thermal performance.
- To remove dependence on the combustion chamber geometry and hence allow easier adoption and potentially higher compression ratio.
- To reduce the calibration effort by removing the possibility of arc formation.
- To reduce cost and complexity of the required electronic system.

The ultimate ignition performance of these optimised igniters is not quite as good as the streamer-type igniter, but this is offset by reduced cost and increased robustness; not only in thermal, mechanical and electrical considerations, but also against sensitivity to calibration and operating conditions. These plug designs may additionally have the described features applied to downsize to 10mm thread body, as described above for the streamer plug. For these reasons this type of design can make an attractive solution in real applications.

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