Ten years of research on electrostatics at the University of Grenoble 1942–1952

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The emphasis is on the practical development and application of electrostatic generators, rather than on theoretical considerations.

The small cylindrical compressed-gas generators with conducting segments proved very satisfactory for powers of the order of 30 W at voltages of 70 kV. In attempts to increase the output multiplate generators with conducting segments were evolved which reached 750 W at 250 kV, but beyond this range difficulties of mechanical construction proved formidable. After disproving the current view that charge slip was responsible for the low output of moving insulator machines, a cylindrical generator of this type was constructed with highly encouraging results.

Further development continues.

Research on electrostatics was started at the University of Grenoble on the initiative of the author at the end of 1942. The work was carried on with very little assistance, and despite very great difficulties, until the end of the occupation in 1945. At that date researches had proved so promising that it was decided to set up a special laboratory at Grenoble for development.

At the end of 1946 a private company was formed in Grenoble for the practical exploitation of patents and inventions arising from the work at the University. (Société Anonyme de Machines Electrostatiques or SAMES). This Company has developed rapidly and keeps in close and constant contact with C.N.R.S. (Centre National de la Recherche Scientifique) at the University. In 1951 a branch company was formed in America, SAMES Inc., with the object of co-ordinating the work of the French company and the numerous interests in electrostatic devices.

STATE OF THE ART REGARDING ELECTROSTATIC MACHINES IN 1942

In 1942 the only work of importance on electrostatic machines was that of Van de Graaff and of Trump, who for six years had been developing the belt type of generator. It was not the author's intention to enter the field in competition with the belt generator but rather to develop the principles on which electrostatic machines functioned in a manner which would make them useful in numerous industrial applications where up to that time they had been completely neglected. Actually, there are numerous applications which require voltages between 10 000 and 200 000 V which are easy to realize with the old electrostatic machines; such equipment had never been used because of its low power and erratic operation.

It was natural, therefore, to consider whether it would be possible to perfect the belt type of machine or whether one should attempt some entirely different construction. In 1942 the belt type machine had near enough reached its maximum performance. This performance was remarkable in the magnitude of the voltage it could produce but, despite the use of compressed gas known since 1886, the power produced remained relatively small considering the size and cost of the machine. This, of course, was of little importance for the applications envisaged by Van de Graaff, whose main object was to produce very high voltages for nuclear research, voltages which it was very difficult to obtain by other means. For applications at lower voltages such as 100–200 kV a small belt machine had proved incapable of competing with other systems. According to the literature on the subject the belt generators had attained their limit because it appeared impossible to increase to any extent the mechanical forces to which the belt was subject or to increase its speed. Indeed, in all electrostatic generators the electric power developed necessarily depends on the work done against the electrostatic forces applied to the moving member carrying the electric charge. The power is determined by the work done against these forces per second, i.e. by the velocity of the moving part. However, there was no question of increasing the belt velocity in the Van de Graaff machines, since the friction of the belt in the compressed gaseous medium would have reached very considerable proportions. The frictional losses increase as the cube of the velocity so that even a slight increase would hardly be practicable.

It did not appear that there would be any possible way of increasing the electrostatic forces on the belt. According to current knowledge the density of the electric charge carried by the belt remained very limited, even in a compressed gas medium, and the electric field acting on this charge density had already been pushed to considerable values, approaching the limit imposed by breakdown. In the best designs of apparatus the useful forces acting on each square centimetre of the belt reached about 600 dynes. The speed was of the order of 25 m/sec and the power was only about 0·15 W/cm^2 of the belt surface.

However, it seemed that much larger powers should be possible. The charge density on the surface of an electrified body is limited only by the ionization of the surrounding gas. The critical field strength producing this ionization is approximately proportional to the pressure, so that the surface charge density should increase in the same way. Accordingly, a machine working at a pressure of 20 atm in air ought to give a current about fifteen times as great as at atmospheric pressure. Again, the voltage which can be applied between the conductors, being proportional to the field strength between them, ought also to be more or less proportional to the pressure. Hence, the power of an electrostatic machine ought to increase approximately as the square of the pressure or, more accurately, should be proportional to the square of the maximum field strength to which the gas can be subjected. This field strength or dielectric strength of the gas is known up to pressures of several tens of atmospheres, so that it should be possible to predict the power of an electrostatic machine at say 20 atm and it should then be around two hundred times greater than that at atmospheric pressure. The belt type machine did not in any way follow this law. The power at the highest pressures did not reach more than five or ten times that at atmospheric pressure, even under the most favourable conditions.

The reasons for this enormous difference were not very clear. Many authorities attributed it to defective adherence of the electrostatic charges to the belt, a difficulty which prevented the belt from carrying, under voltage, the charge density permitted by the dielectric strength of the medium. It was presumed that the charge suffered displacement or slip along the belt as a result of the electric field produced by the poles of the machine. It had been noted in effect that the current produced by a belt machine under short-circuit conditions could be quite considerable, but generally fell off very rapidly as the potential delivery by the machine was increased. It appeared, therefore, that the tangential field created along the belt caused a flow of the charge along the belt by reason of its poor adherence, and this flow was responsible for the considerable drop in current with increase of voltage.

INITIAL EXPERIMENTS WITH CONDUCTING ELEMENTS

In view of the results just discussed it appeared that there would be little point in attempting to perfect the belt type of apparatus in order to increase its power, and so an arrangement was sought which would permit the use of considerable electrostatic forces without the risk of the charges being displaced. The author accordingly considered the use of conductors. The electrostatic forces exerted on a conductor are always perpendicular to its surface and so movement of the charges is impossible. Only ionization of the ambient gas can cause the disappearance of charges and forces, and therefore one ought to be sure of obtaining considerable forces under reasonable pressures. In air at atmospheric pressure the critical field strength is around 30 kV/cm and the maximum force 0·4 g/cm^2, which is very small, but at a pressure of 30 atm in air the critical field is at least 600 kV/cm, i.e. twenty times larger. The force per square centimetre is accordingly four hundred times as great, and therefore could reach 160 g/cm^2 which would be of some interest. From these considerations it should follow that an electrostatic machine, where the moving members are conductors, ought to have a power increasing as the square of the dielectric strength of the gaseous medium, and which might, for example, be four hundred times at a pressure of 30 atm compared with that at a pressure of 1 atm in air.

At the beginning of the author's researches an attempt was made to verify these theoretical conclusions with a very simple piece of apparatus which was a replica of a very old machine constructed by the German Professor Toepler in 1865 (Fig. 1). This apparatus consisted simply of an insulating disk on which were fixed two semi-circular conducting segments separated from each other and which passed in front of a fixed inductor. By the action of two brushes each conducting sector was connected to earth when its capacity with respect to the conductor was a maximum, and brought into contact with an insulated terminal when its capacity was a minimum. Thus, it became charged with a certain quantity of electricity under zero potential, this being given up to the receptor at a greater potential. The apparatus therefore constituted an actual generator. However, it was evident that one would not expect very good results by putting such an apparatus under compressed air because the intense electrostatic forces which had been expected were actually exerted across a section of the elements, and this section, in the original Toepler apparatus, was too small to allow reasonable forces. In these old machines the elements had taken the form of simple sheets of tin foil of negligible thickness.

A mathematical study was then undertaken to determine the optimum proportions of the moving elements, taking into account the distance between each element and the fixed inductor, so as to assure throughout a uniform dielectric stress on the ambient medium. This study showed that it was necessary to give the element a thickness equal to the distance of its separation from the inductor in the case when the conductor is charged on only one side (Fig. 2*a*), and equal to double this distance when the conductor is under stress on

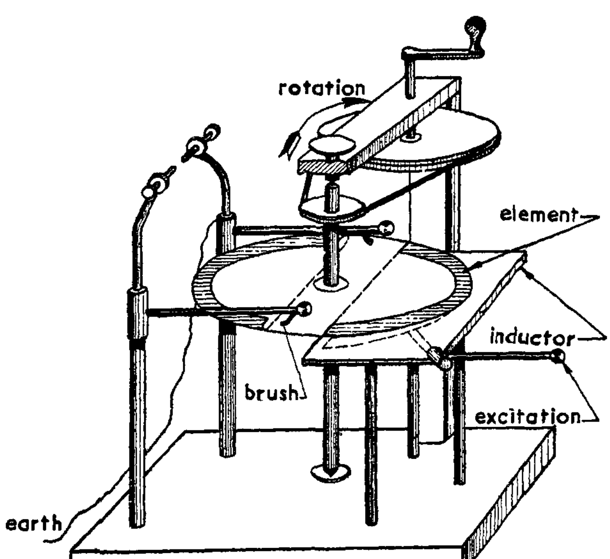

Fig. 1. Toepler's original machine

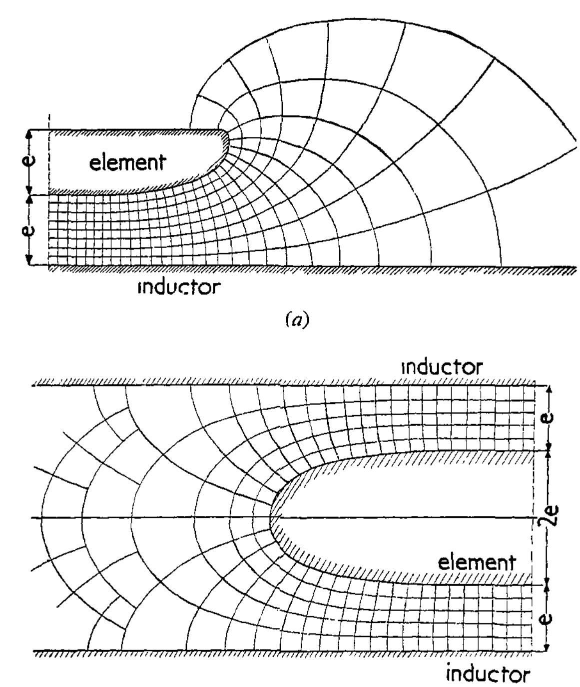

Fig. 2. Theoretical profile for constant dielectric stress
(*a*) Conductor charged on one side.
(*b*) Conductor charged on both sides.

both sides (Fig. 2*b*). When the thickness of the element is chosen in this way, and when the section is given the ideal profile, which one can calculate theoretically, one can be sure of making use, without risk of ionization, of all the potential energy of the condenser formed by the element and by the inductor. As the potential energy of the condenser increases as the square of the dielectric strength of the gaseous medium the power of the machine ought to increase likewise for a given speed.

Fig. 3 shows the apparatus constructed by Morel in 1943 according to the above principles and which completely

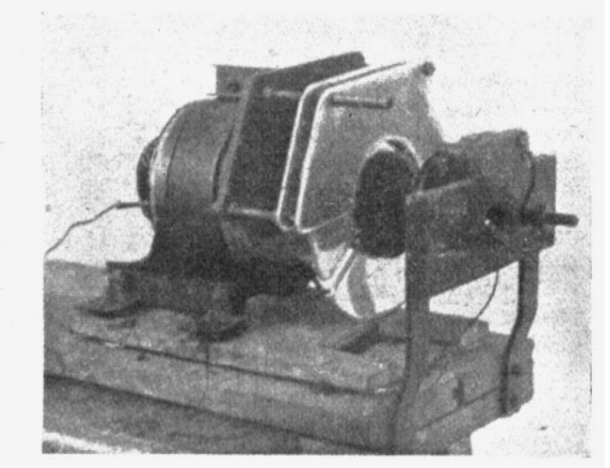

Fig. 3. Morel's apparatus

verified these theoretical conclusions. The power was in fact multiplied by a factor of two hundred and fifty when the pressure changed from 1 to 30 atm, a factor which represents exactly the square of the ratio of the dielectric strength of air between plane aluminium electrodes at 1 and 30 atm. Thus it had been demonstrated that the power of electrostatic generators can, by means of correct construction, be effectively proportional to the square of the dielectric strength of the gas, and the production of considerable powers at practicable pressures became possible.

The first apparatus constructed by Morel had on account of its small dimensions quite a small power, 6 W at a speed of 1500 r.p.m. and at a pressure of 20 atm. In order to investigate the above principles further, the construction of a much bigger machine was undertaken (eight elements per disk instead of two, and five disks in place of one). Despite the great difficulties in obtaining materials this apparatus was finished at the beginning of 1944, and the experiments were conclusive, taking into account the imperfections of its construction. This generator developed 250 W at a speed of 1500 r.p.m., i.e. an output of 5 mA at a voltage of 50 kV. Its efficiency was very high, of the order of 80%, the only losses being due to the unavoidable friction of the moving elements in air compressed at 25 atm.

FIRST INDUSTRIAL APPLICATIONS: CYLINDRICAL GENERATORS WITH CONDUCTING SEGMENTS

At the end of the war contacts between industry and the laboratory became closer. It became evident that a small, very light generator giving powers of several watts and proving reliable in operation would be capable of several applications. It was thought that it could be used as a portable generator for precipitation of powders and mists in the treatment of crops; for supplying high voltage to infra-red image converters. These applications appeared to be very suitable for the new machines, and the construction of very small generators based on the same principles as the disk machines discussed above was undertaken in 1946. On account of the smallness of the power required, the stator and rotor were made of segments having a cylindrical shape instead of plane elements and multiple disks (Fig. 4). Several

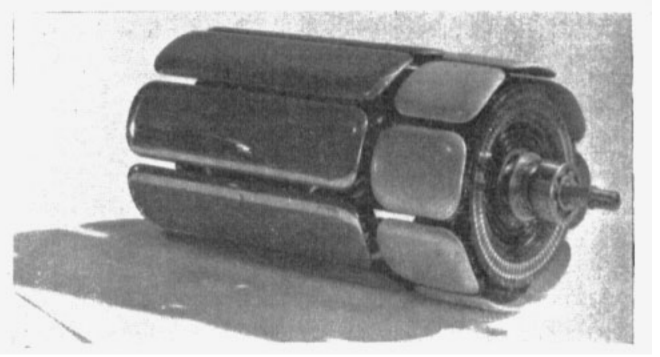

Fig. 4. Rotors of a cylindrical generator

On left: principal rotor; *on right:* exciter rotor; diameter: 14 cm; length of principal rotor: 18 cm; clearance between stator and rotor: 0·25 cm; voltage: 70 kV; current: 0·4 mA at 1500 r.p.m., 0·8 mA at 3000 r.p.m.; gas used: air at 25 atm.

prototypes were tried out in the laboratory giving voltages between 20 and 60 kV with an output of the order of 0·1 mA. The main problem with such generators was that of providing a mechanical drive, by hand for example, through a gas-tight packing which would be very simple and yet avoid loss of gas. Here the first practical success of these new electrostatic generators was achieved. Extremely successful trials were carried out on the spraying of crops with dust. At the same time it was possible to replace by a small generator weighing about 2 kg the enormous system of rectifiers which had been employed by the Germans for supplying infra-red image converters.

At this time SAMES started to produce a small series of these generators. There were two main types: one producing 0·1 mA, the other 0·4 to 0·8 mA according to speed (the high speed could not be maintained permanently because of the rapid heating of the compressed gas). For both the voltage was 60 to 70 kV. Two other notable achievements of SAMES deserve mention: the arrangement of electrostatic generators in series, and the development of an electrostatic ignition device. The series coupling of generators permits the production of voltages which up to the present time have reached 250 kV.

In a very different field, considerable effort had been devoted to the provision of a special generator for ignition in internal combustion engines. This generator (Fig. 5) provided a very satisfactory solution of the problem of ignition and is considered to be superior to the methods already known. This machine has the important advantages of being completely independent of batteries; of providing sparks of the same intensity at all speeds; and most important of all, of providing ignition totally independent of the insulation resistance of the sparking plugs, of oil films, etc. The minimum sparking plug resistance at which a coil will operate is of the order of 500 000 Ω. With this new device it can be as low as 250 Ω. This electrostatic ignition system is most interesting and has created abroad, particularly in America, sufficient interest to make industrial development on a large scale probable.

At the same time SAMES continued to manufacture and improve considerably the very light generators for providing power for infra-red converters which, however, cannot be described in detail for reasons of secrecy. All these machines, as will be seen from the figures, are of the cylindrical type; rotor and stator are formed of segments of cylinders and are separated from one another by a distance of the order of

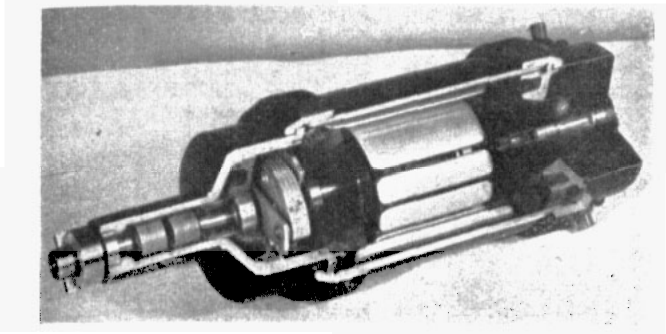

Fig. 5. Electrostatic generator for ignition in internal combustion engines

1 to 3 mm. Much could be said on the practical problems raised in the development of such machines, many of them entirely novel, and particularly on the very successful use made of new plastic materials such as Araldite.

While indicating briefly the successes of these new generators, one ought at the same time to point out the limitations and defects. The field of application for these generators lies in the realm of voltages between 20 and 200 kV, particularly where reliable operation is needed. They can be driven equally well by petrol engine, by crank or by electric motor. They do not constitute any danger, and they can be multiplied for higher voltages without any risk. These are considerable advantages which justify the good reception they have had in several applications.

Unfortunately, however, the electrification of chemicals for the treatment of crops has not succeeded for economic reasons. Electrification should have made it possible to save three-quarters of the chemicals normally used for treatment. Unfortunately, farmers were not disposed to buy relatively expensive apparatus in order to effect such an economy, the chemicals being maintained at a low price by the Government. Thus the commercial exploitation of the electrification process for the treatment of plants has been hindered.

From the figures quoted it is evident that the current in the above machines is relatively small, in all cases less than 1 mA, and this is a limitation. It results from the use of the cylindrical type of machine which does not, as in the case of multiple disks, provide much surface area. Another defect appeared during service: the brush gear, while advantageous for excitation of normal machines, suffers accelerated wear as a result of the inevitable sparking, wear which limits the life of a generator to a maximum of a thousand hours. In an ordinary machine it is only necessary to replace these contacts and remove the dust produced, but this replacement is not so easily made in electrostatic generators since the gas-tight cylinder must be opened.

In view of the relatively small power limit of the cylindrical generator, work on the disk type of machine was started again in 1946, initially on the multiple disk apparatus used by Morel. Funds were provided for a model of considerable size (Fig. 6), consisting of 6 disks each of 12 sectors which would furnish 2 to 3 mA at 250 kV. This apparatus was in operation at the end of 1947, firstly as a single unit and then as two units of opposite polarity giving double the voltage. This machine has been very useful in the laboratory as a source of high tension for numerous experiments. In addition, it has been lent for a year to the Electricité de France to carry

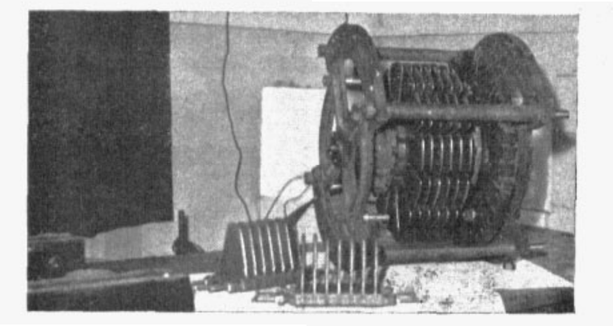

Fig. 6. Complete multiple disk apparatus. The stator is removed in sections

External diameter of rotor: 39 cm; clearance: 0·4 cm; voltage: 250 kV; current: 2 mA at 750 r.p.m.; gas used: air at 30 atm.

out investigations on the effects of corona on d.c. overhead lines.

Though the results obtained with the disk type of machine were satisfactory, great difficulties were encountered in constructing the rotating parts. These parts are made of metal, have considerable weight, and are supported by flanges of plastic insulating material keyed to the shaft. Hence the geometrical positioning of the elements on the rotor depended on pieces whose mechanical rigidity was relatively weak. Centrifugal forces and other causes slightly displaced the groups of sectors because of the deformability of the insulating flanges. As a result, despite the fact that it was possible to adjust the individual position of each group of elements initially, this position was not maintained, and hence it was not possible to work to the clearance between the stator and rotor originally intended. The separation at places became greater, at others less, and these became regions which limited the value of the power by setting up discharges between the segments of the stator and those of the rotor. It was necessary to readjust the elements fairly frequently (once a month), a matter acceptable in a laboratory but impossible in an industrial machine. Experience having shown the importance of this mechanism and of geometrical factors in general, a study was undertaken of a multiple disk machine in which all insulating parts were eliminated from the rotors. The resultant rotor, called a "Monobloc" (Fig. 7) consisted

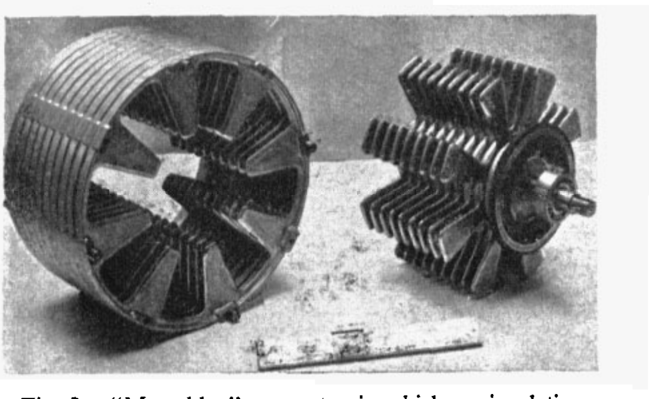

Fig. 7. "Monobloc" apparatus in which no insulating parts are used

On left: stator; *on right:* rotor.

of a stack of entirely metal disks, each disk comprising eight elements. A certain number of disks (five to ten) were screwed tightly to the axle. It was hoped in this way to obtain a much more accurate positioning of the elements and to avoid variations of separation in use. The model was built in 1950 and was designed for 70 kV at 10 mA. During its construction it was found that the alignment for parallelism and equidistance of the elements did not attain the standard of precision necessary, because although individual errors were themselves small (1/100 mm) these became additive in the construction of the complete stack. In the end the structure was no better than that of the previous model, and since no form of adjustment was possible it had to be admitted that the construction of an accurate multiple disk machine presents extremely difficult problems. Another disadvantage also appeared: sparks between metal surfaces are a random phenomenon depending on the presence of accidental impurities in or on the surface and so the risk of sparking between surfaces becomes greater as their area increases. Hence for a disk machine where the surface area is considerable the electric field, which can be maintained with certainty between the stator and the rotor, is measurably less than for small cylindrical machines.

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It thus appeared that machines with conducting sectors and multiple disks would prove difficult to realize on an industrial scale, and that it would not be possible to obtain powers greater than a few hundred watts, which was about the limit of the cylindrical machines with conducting sectors under construction.

At this time the attention of the author had been directed to the divergence of results obtained from different types of machines in which the moving elements carrying the charge were of non-conducting material. It appeared that the power limit was higher when insulating disks were used instead of belts as in the Van de Graaff machine. Several publications on machines with insulating disks claimed performances undoubtedly superior (in relation to surface area) to those of belt machines. From these contradictory results it could be concluded that the theory of slip or longitudinal displacement of the charges on the insulating belts was perhaps inaccurate and that the limitations of such machines resulted from some still unknown factor.

For this reason, at the beginning of 1950, the construction of a very simple experimental machine with an insulating disk was started at C.N.R.S. Its purpose was to investigate the question of charge slip. Experiments showed that there was no reason to suspect the adherence of electric charges to the insulator. The apparent slip could be explained by local ionization of the compressed gas. This ionization was due to the presence of parasitic electric fields proportional to the output voltage.

These conclusions, contradictory to generally accepted opinions, gave rise to the hope that it would be possible to use insulating transport disks under much greater forces, and hence obtain considerable increase in power. It is not possible to review the numerous experiments and difficulties by which the ensuing designs were eventually reached, but at this stage a number of principles can be enunciated which permit a very simple electrostatic machine to be constructed with insulating moving members and having an efficiency greatly superior to that of other systems. The moving insulating parts must have a geometry which will avoid any kind of vibration whatever during movement. The cylinder is the only shape which will satisfy this condition. The stator must be another smooth cylinder separated from the moving cylinder by a uniformly small distance, 0·2 or 0·3 mm. The static cylinder should be made of some material of constant resistivity of the order of $10^{11}\ \Omega$ cm. Finally the ambient gas, instead of being electronegative (air, freon, etc.), should be pure hydrogen at a pressure of 10 to 20 atm. It is not possible to state briefly all the reasons which justify this choice since some are not yet completely known. In particular, the fact that pure hydrogen allows the current to pass very easily from a comb and acts as a very good insulator in other respects seems inexplicable. These two properties, apparently completely incompatible, are not exhibited by any other gas. Fig. 8

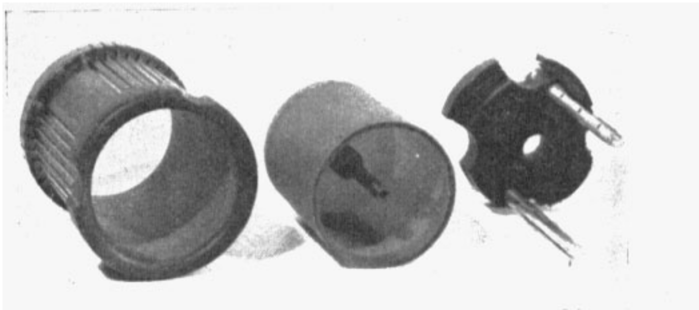

Fig. 8. Experimental insulating cylinder generator capable of producing 70 W

On left: Bakelite stator; *in centre:* Araldite rotor with axis; *on right:* supports for combs; clearance: 0·025 cm; diameter of rotor: 7·8 cm; voltage: 200 kV; current: 0·35 mA at 3000 r.p.m.; gas used: hydrogen at 20 atm.

shows the actual machine which produced a power of 70 W at 200 kV at a speed of 3000 r.p.m. The rotor and stator are simple plastic cylinders, the one an insulator and the other slightly conducting. The diameter is about 8 cm. It will be noted that unlike the belt machine and those described earlier, the loss due to friction in the compressed gas is negligible because of the low density of the hydrogen and the peripheral velocity is limited only by the centrifugal force. It can therefore be very much greater than formerly, all the more so because there is no mechanical friction between the rotor and the combs. All these advantages allow powers greater than 1 W/cm^2 of the effective area of the cylinder to be obtained at voltages of the order of 200 kV. Since the middle of 1951 results obtained in the laboratory have been so encouraging that improvements to multiple disk machines have been abandoned and all the available resources have been turned towards the perfection of the insulating cylinder type of machine. These machines present considerable advantages of simplicity, of increased power and voltage, and the connexion of a small number in series ought to produce voltages as large as those obtained with the belt machines, in addition to very much greater power.

Naturally, difficult practical problems have arisen for which complete solutions have not yet been realized: the moving cylinder is affected by the bombardment of the ions, and it is difficult to find a material whose resistivity is both high and well defined. For possible further developments it can be noted that the insulating cylinder type of machine can be made to function with two fluid dielectrics instead of only one. Pure hydrogen could be used on one side of the cylinder in the space where ionization takes place, and another fluid of better dielectric properties such as nitrogen, or even a liquid, could be used in the space between the stator and rotor. The power would then be found to be increased by the ratio of the maximum of the electric fields which will exist in the fluid to the maximum field in the hydrogen. Experiments have already succeeded in which oil has been introduced into the interspace. It seems that this is a development which might lead to the production of powers of relative importance.

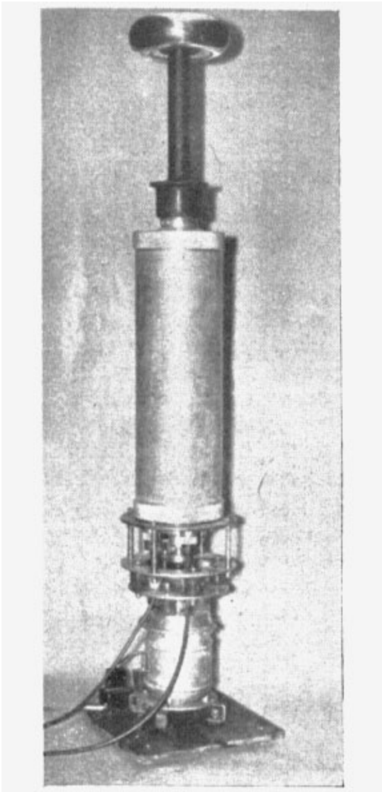

Fig. 9. Insulating cylinder generator capable of developing 230 kV

At the bottom: motor; diameter of gas-tank: 22 cm; voltage: 230 kV; current: 1·5 mA at 3000 r.p.m.; gas used: hydrogen at 15 atm.

CONCLUSION

It can be seen that during the last ten years the research at the C.N.R.S., and the work at SAMES, have systematically explored the practical possibilities of electrostatic generators from all angles. At the beginning efforts were centred solely on the machines with conducting segments, insulating segments having appeared impracticable for reasons which were eventually shown to be groundless but which, at that time, were universally accepted. These investigations have not made it possible to exceed powers of more than a few hundred watts in industrial equipment because of unexpected difficulties of mechanical construction. On the other hand, in the domain of small machines it has been possible to make apparatus on a practical scale which will function reliably and maintain a definite polarity. An ignition system for internal combustion engines represents perhaps the greatest achievement. After having studied the use of conducting segments for eight years and having finally decided against their use for high powers, a scientific study of insulating charge transporters has revealed that the limitations of belt machines or those with insulating disks previously assumed were completely false. This conclusion is perhaps the most noteworthy advance made at this electrostatic laboratory. The aim of the work has not been confined to demonstrating the limitations of accepted ideas, but has endeavoured to pose new principles on which the insulating cylinder type of machine can be developed. At present these machines (Fig. 9) will give voltages above 200 kV with an output of 1 to 2 mA, i.e. they already provide powers of the same orders as the most advanced machines with conducting disks, and therefore it may be hoped that the limits of this new system of generators are still a long way off.

DISCUSSION

Mr. J. H. McGuire: I also am interested in the electrostatic generator for ignition in internal combustion engines, and I should like to ask about the engineering aspect of its application to variable speed engines and its operation on starting. Is the generator driven at a constant speed, with a limitation on the rate of delivery of sparks, thus giving a constant equilibrium voltage? Alternatively, is the generator voltage not allowed to reach equilibrium but driven by the engine so that generator speed compensates for increased spark delivery requirement, again giving an approximately constant voltage? This latter operation, if possible, is near to the ideal of efficiency.

Dr. E. C. Craven: What does Professor Felici imply by the term "pure hydrogen"? In hydrogenation work one is pleased if significant impurities (carbon monoxide in particular) can be reduced to a few parts per million. What are the significant impurities in the electrostatic application and how are their amounts determined?

Mr. E. S. Shire: Firstly, purity is a relative term and electronegative impurity of one part in a million rapidly traps electrons at atmospheric pressure and more so at high pressures, as is shown by the difficulty of extracting electron pulses from high-pressure hydrogen ionization chambers used in nuclear physics. In Professor Felici's generators, hydrogen might behave as pure hydrogen near the corona points, where the electron density could be high, and as impure hydrogen elsewhere.

I should like to ask: how stable is the voltage given by the generators?

Dr. R. Fürth: Is it really justifiable to call these machines, which generate considerable electric currents, "electrostatic"? I think the word should be restricted to describe phenomena of *static* electricity. I suggest that these machines should rather be called "electric induction generators" as distinct from "electromagnetic generators."

Author's reply: In our earliest experiments on ignition, the generator was driven at a constant speed by a small d.c. motor fed by the battery. We found this arrangement inconvenient in practice, for it requires constant generator voltage, which is not a natural feature of any electrostatic machine. So we turned to a generator driven by the explosion engine itself, thus giving constant spark delivery independently of the speed. The sparking voltage remains fairly constant from 1 r.p.m. to 3000 r.p.m.

Our "pure" hydrogen may contain one part in 10^4 of electronegative impurities. It is purified in the hydrogen liquefier of the University. We felt no need for any further increase in purity. That may be explained, as pointed out by Mr. E. S. Shire, by the very high electron density near the ionizing blades, which is sufficient to saturate the impurities, making them harmless in practice.

The voltage stability has not yet been studied. The natural voltage fluctuations may be of the order of 1 %. No ripple, however small, can be detected.