June 23, 1964 G. FONDA-BONARDI 3,138,019

PLASMA ACCELERATOR FOR WIND TUNNEL

Filed Nov. 7, 1960 3 Sheets-Sheet 1

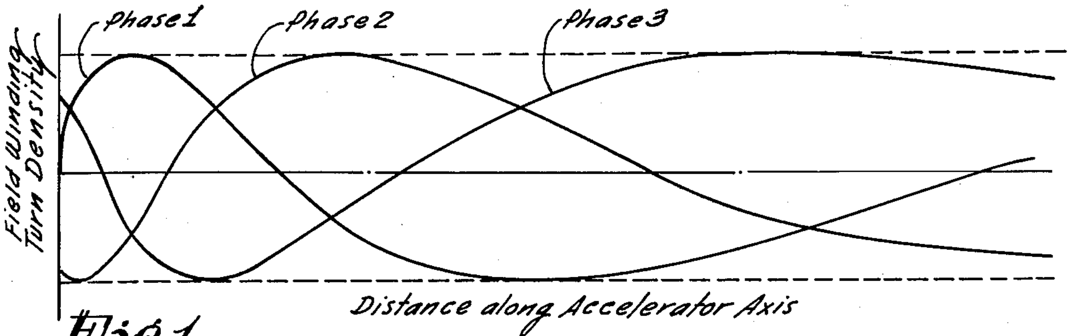
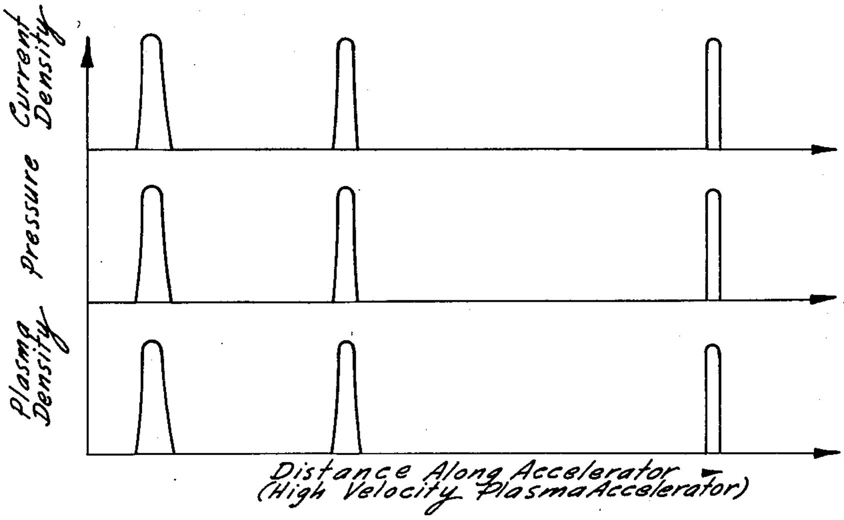


Fig. 1

Fig. 2



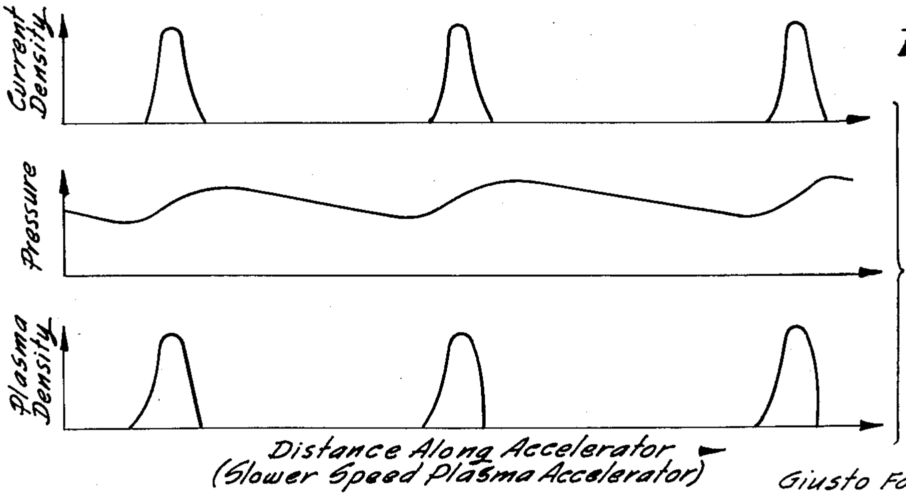


Fig. 3

INVENTOR:
Giusto Fonda-Bonardi

By Alan C. Rose
Attorney

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PLASMA ACCELERATOR FOR WIND TUNNEL

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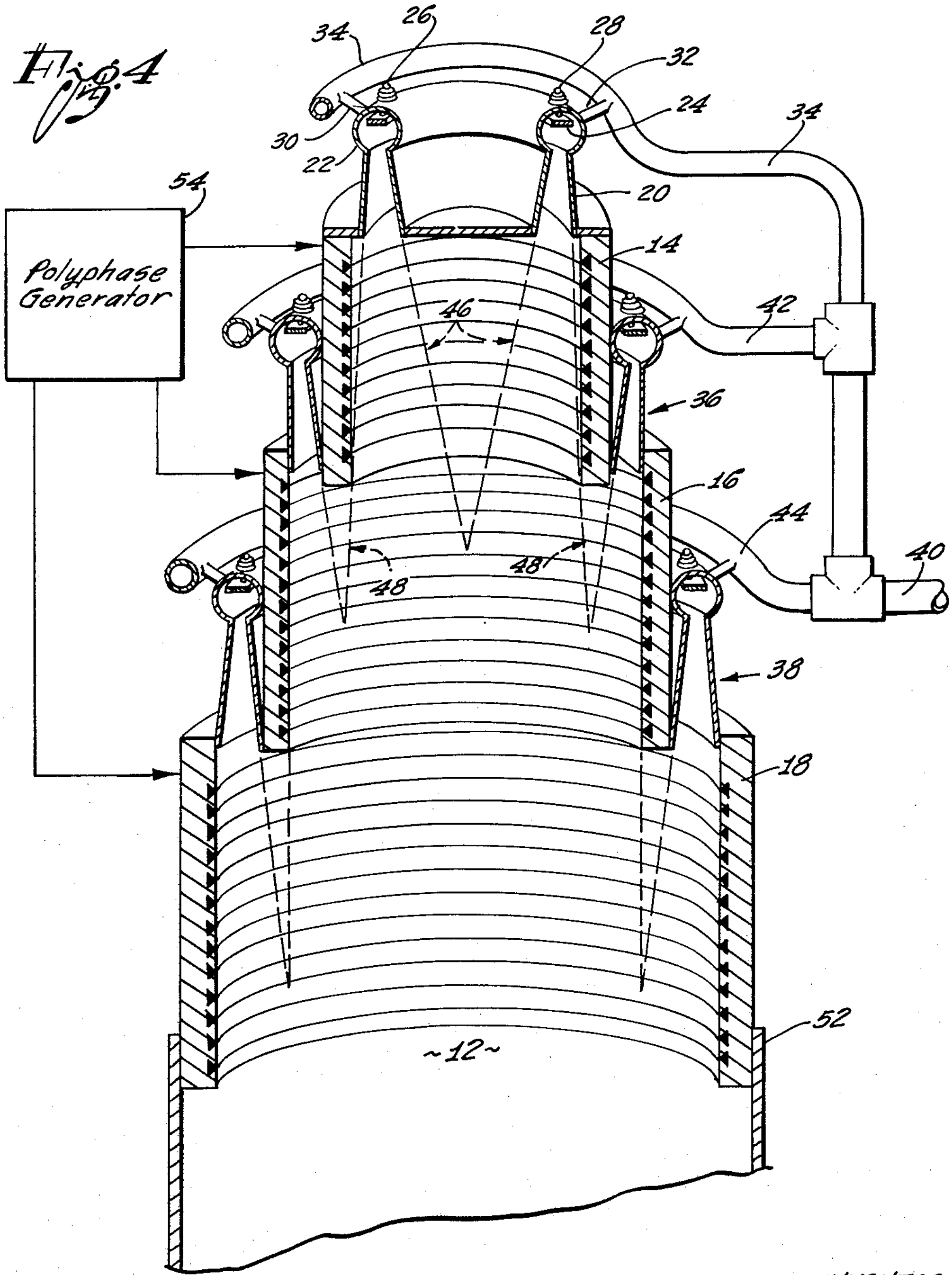
Fig. 4



INVENTOR:
Giusto Fonda-Bonardi

By Alan C. Rose
Attorney

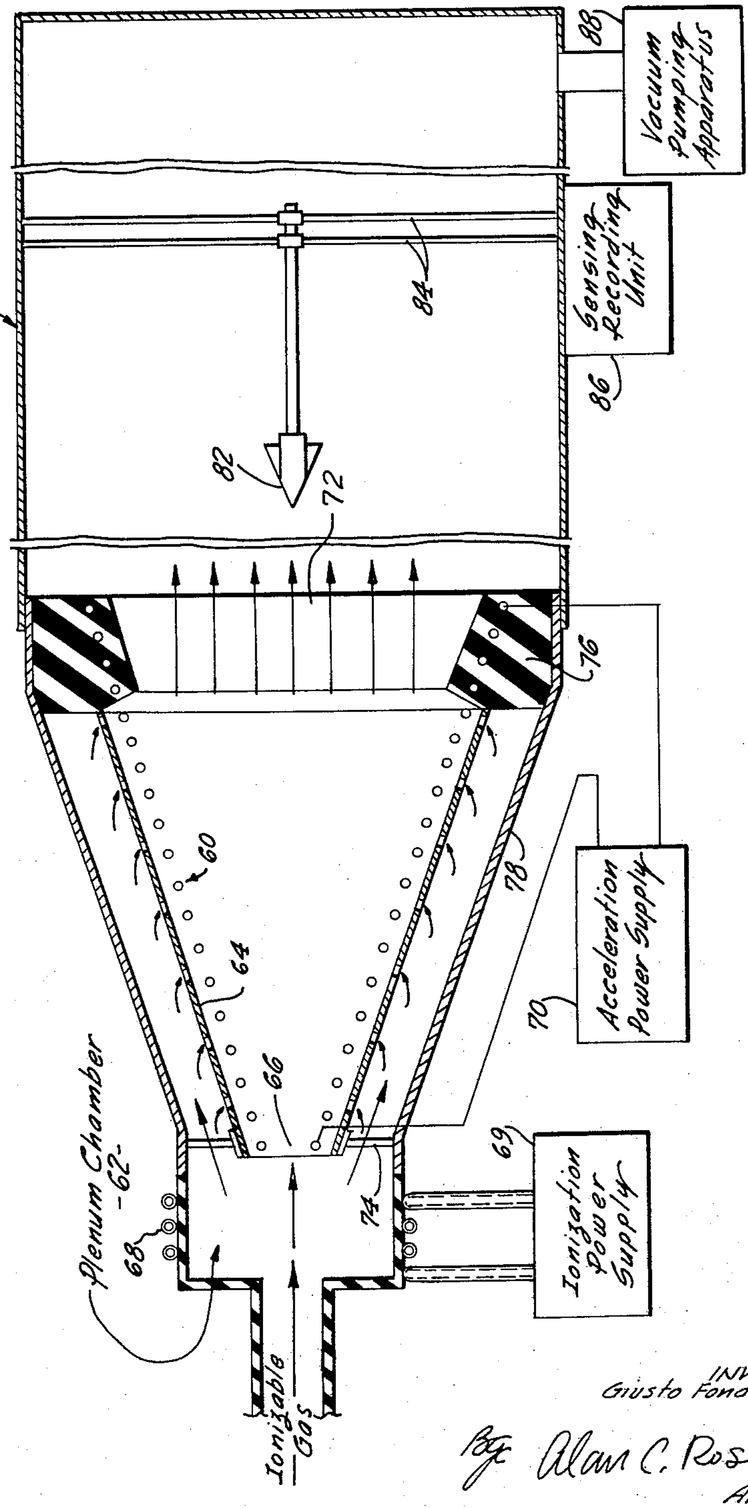


Fig. 5

INVENTOR.
Giusto Fonda-Bonardi

By Alan C. Rose
Attorney.

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PLASMA ACCELERATOR FOR WIND TUNNEL

Giusto Fonda-Bonardi, Los Angeles, Calif., assignor to Litton Systems, Inc., Beverly Hills, Calif.

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This invention relates to plasma accelerators, and more particularly to accelerators having a large capacity.

For certain applications such as supersonic wind tunnels, it is necessary to accelerate relatively large masses of air to velocities well above the velocity of sound in air. Plasma accelerators have been proposed heretofore which are capable of accelerating gas to the required speeds. In this regard, reference is made to Siegfried Hansen patent application, Serial No. 723,018, filed March 21, 1958, entitled "Plasma Accelerators," now Patent No. 2,992,345, granted July 11, 1961, and assigned to the assignee of the present patent application. The accelerator of this prior application included an elongated electromagnetic structure of constant cross-section or of convergent geometry, and arrangements for providing an accelerating field along the length of the magnetic structure to accelerate the plasma. While this structure was well adapted for accelerating pulses of highly ionized plasma to very high velocities, approaching the velocity of light, its capacity for the economical acceleration of large masses of air is severely limited.

Accordingly, a principal object of the present invention is to increase the capacity of plasma type gas accelerators.

Before proceeding with a description of the present invention, it is considered desirable to define the word "plasma" which will be frequently used in the present specification. As herein utilized, the term "plasma" designated a volume of gas in which an appreciable percentage of the atoms are ionized, but which contains the detached electrons within the same volume so that the gas as a whole is substantially electrically neutral. Except for mechanical rigidity, therefore, a plasma is very similar to a metal in its properties since the detached electrons remain uncombined for relatively long periods and can move about at random within the boundaries of the gas volume. In fact, it can readily be demonstrated that the electrical conductivity of a relatively highly ionized plasma can actually exceed that of such good electrical conductors as copper and silver.

In accordance with one illustrative embodiment of the present invention, the object set forth above is achieved by providing an elongated electromagnetic structure of progressively increasing diameter, to which ionizable gas is supplied at succesive points along its length. Thus, for example, the coil structure may include a first short accelerator of small cross-section, followed by another accelerator of larger cross-section. Gas accelerated by the first accelerator is fed through the center of the second accelerator together with an additional outer "sleeve" of gas supplied to the second accelerator. With increasing coil diameters the magnetic field is only effective to accelerate the enclosed plasma near the coil. Accordingly, the second accelerator operates principally on the peripheral sleeve of gas and brings it up to the velocity of the inner core which was accelerated by the first accelerator.

When it is desired to have larger cross-sectional areas of accelerated gas, three or more successive accelerators may be employed in tandem, with gas being introduced peripherally at the beginning of each short accelerator. Alternatively, a single long accelerator of generally conical or funnel-shaped cross-section may be provided, with arrangements for introducing gas along its length. From one viewpoint, the funnel-shaped accelerator may be considered to be the limiting case of the tandem electromagnetic structure, as the number of coils is progressively increased and the length of each coil is correspondingly reduced.

In accordance with an important feature of the invention, therefore, a high capacity plasma accelerator includes an elongated electromagnetic structure having a small input cross-section and an increasing cross-section toward its output, and also includes arrangements for introducing ionizable material into said structure at its input and at least one additional point, or region, along its length.

In accordance with collateral features of the invention, the electromagnetic accelerator structure of the preceding paragraph may include a plurality of coils of progressively increasing diameter, or it may be a single structure of progressively increasing diameter.

Other objects, features and advantages of the invention will become apparent from a consideration of the following detailed description and from the drawings in which:

FIG. 1 is a plot representing the turns distribution of a poly-phase field winding of a linear plasma accelerator;

FIG. 2 represents the plasma density, the pressure, and the current density of a high velocity or "hard" plasma accelerator plotted against distance along the length of the accelerator;

FIG. 3 shows a similar set of plots for a slower speed, or "soft" plasma accelerator;

FIG. 4 represents a plasma accelerator, in accordance with the present invention, in which gas is introduced at several zones along the length of the accelerator structure; and

FIG. 5 is another embodiment of the present invention in which a generally conical accelerating structure is employed.

Referring more particularly to the drawings FIG. 1 represents the distribution of turns along the length of a hollow cylindrical plasma accelerator. With a polyphase energizing signal, an accelerating field is produced within the electromagnetic structure. When ionized gas is introduced into the hollow coil structure at one end, it is accelerated down the length of the coil and ejected from the other end at high velocity. The operation of such an accelerator is disclosed in detail in the co-pending application of Siegfried Hansen cited above.

Depending on the rate of acceleration and the pressure within the accelerator, two distinct modes of operation are possible: in the case of very high accelerating forces, the gas plasma will be broken into discrete plasma clouds or pulses which are separated from one another by regions which are essentially evacuated. Such an accelerator is known as a "hard" accelerator. If lower accelerating forces are employed, however, the ionized zones of plasma merely act as pistons and carry additional gas which may not be ionized between the concentrated clouds of ionized gas. Such a relatively slow speed plasma accelerator is known as a "soft" accelerator.

The plots of FIGURES 2 and 3 represent operating conditions for "hard" and "soft" accelerators, respectively. The upper and lower curves of FIGURES 2 and 3 are not significantly different, with the exception that the current density and plasma density peaks tend to be more sharp and less diffuse in the case of the hard accelerator of FIG. 2 than in the case of the soft accelerator of FIG. 3. With regard to the central pressure curve in FIGURES 2 and 3, however, the distinct pressure peaks in the hard accelerator are clearly visible in FIG. 2, whereas the pressure gradient between successive pulses produces the generally sawtoothed characteristic shown in the central plot of FIG. 3. The physical reason for the discontinuous pressure peaks in the central characteristic of FIG. 2, for the hard accelerator, is in part a result of the physical impossibility of having negative pressures, when the accelerating force exceeds the available pressure force.

By way of example, the following two sets of data for hard and soft accelerators, respectively, have been developed. They will be set forth in the following Tables I and II:

Table I

Average mean flow	1.2×10^{-7} kg./sec.
Pulse repetition rate	60 cycles.
Output velocity	10^5 meter/sec.
Mass of each plasma burst	2×10^{-9} kg.
Energy of each burst	10 joule.
Length of accelerator	4 meters.
Number of field windings	160.
Duration of acceleration of each burst	20 microseconds.
Duty cycle	0.0012.
Average acceleration	5×10^9 meters/sec.^{2}.
Average mechanical force	10 Newtons.
Average accelerating magnetic field	.05 Weber/m.^{2}.
Average ring current in plasma	200 Amp.
Plasma temperature after pinch	1390° K.
Plasma pressure after pinch	2.91 Newton/m.^{2}.
Pinch radius	1.48×10^{-2} m.
Pulse power demand	500 kw.
Average output power	600 watts.
Rate of heat generation in ring	17.35 kw.

Table II

Output density	4.10×10^{-4} kg./meter^3.
Output pressure	3.73×10^{-4} atm.
Output temperature	349 degrees K.
Output velocity	Mach 20=20×375 =7500 meter/sec.
Output mass	3.07×10^{-2} kg./sec.
Output volume	75 meter^3/sec.
Output area	1×10^{-2} meter^2.
Accelerating power	1020 kw.
Heating power (122° K.–349° K	8.5 kw.
Ion density in rings	99.1%.
Average ion density	17%.
Exciting frequency	10 kilocycles.
Mass of each gas ring	$1.53\times10-6$ kg.
Disassociated charge in each ring	1.7 Coulomb.
Ring current	32.8 amperes.
Electron drift speed	10.5 meter/sec at 0.175 meter diam.
Ring voltage	3.72×10^{-4} volt.
Power dissipated in each ring	1.22×10^{-2} watt.
Peak flux density	0.07 Weber/meter^2.
Average flux at ring	0.05 Weber/meter^2.
Core losses	1.7 watt/lb.
Average acceleration	1.07×10^6 meter/sec.
Duration for 7500 meter/sec. output	6.38×10^{-3} sec.
Length of accelerator	26.0 meters.
Number of rings	127.6.
Power dissipated in rings	1.43 watts.

Expansion nozzle (input to accelerator):

Expansion ratio	40:1.
Input temperature	350 degrees K.
Input pressure	1.492×10^{-2} atm.
Input density	1.49×10^{-2} kg./meter^3.
Output temperature	122 degrees K.
Output pressure	3.73×10^{-4} atm.
Output density	1.07×10^{-3} kg./meter^3.
Output velocity	676 meter/sec.
Output mass	3.07×10^{-2} kg./sec.
Output volume	28.7 meter^3/sec.
Output area	4.24×10^{-2} meter^2.

Table II—Continued

Associated equipment:

Total cooling capacity	1122 kw.=268 kilocal./sec.=1065 B.t.u./sec.
Pump capacity	75,000 liter/sec. at 0.28 mm. Hg.

With regard to the foregoing two sets of data, they are merely illustrative of particular sets of operating conditions for single stage plasma accelerators. The relatively high cooling requirements are particularly to be noted. In the case of wind tunnel operation, tests for relatively short periods of time are often adequate. If prolonged operation is undertaken, however, adequate cooling must of course be provided.

The present invention involves an improvement over the plasma accelerators of the prior art, in which large masses of air may be accelerated by means of a plasma accelerator. FIG. 4 represents one illustrative embodiment of my invention. In the apparatus of FIG. 4, it is desired to produce a large volume of air at the output **12** from the accelerator which has a speed of about 7500 meters per second. This would correspond to approximately Mach 20 under pressure conditions corresponding to an elevation of approximately 200,000 feet.

In the operation of plasma accelerators, the accelerating electromagnetic structure tends to be operative only within a relatively short distance of the electromagnetic turns. Thus, in the case of very large diameter coils, the central core of air is not accelerated to the desired speed and an undesirable variation in the velocity of gas is observed across the output channel from the accelerator. In the arrangement of FIG. 4, three successive accelerator structures **14**, **16** and **18**, are provided which accelerate the central core of air and then successive additional sleeves of air which are introduced between the successive coil structures.

Thus, for example, the central core of air accelerated by the coil structure **14** is provided from the annular nozzle structure **20**. Coupled to the nozzle structure **20** is an annular ionization chamber **22**. Ionization chamber **22** includes an electrode **24** which is energized through a series of conductors **26**, **28** to a potential at which discharge will occur at the relatively low pressure within the chamber **22**. Ionizable gas, such as air, is supplied to the ionization chamber **22** through inlet tubes **30**, **32** from the manifold structure **34**.

A similar gas inlet structure **36** is provided for supplying gas to the space between coils **14** and **16**; similarly, the structure **38** supplies partially ionized gas to the annular space between electromagnetic structures **16** and **18**. With the exception of increased size, the structures **36** and **38** are similar to the structure including the nozzle **20** and ionization chamber **22** described above. Each of the three structures makes a gas tight fit with its associated coil structure. Air is fed from the input line **40** to the manifolds **34**, **42** and **44** associated with the successive gas inlet arrangements. Through the use of a common input conduit **40**, accurate control of pressure to the three structures may be provided. As indicated by the dotted lines **46** within the coil structure **14**, the annular input gas stream from the nozzle structure **20** merges to form a central cylindrical core of gas. Similarly, as indicated by the dotted lines **48**, the gas from the ionization structure **36** merges with the gas accelerated by the upper electromagnetic structure **14**. Thus, at the output **12** from the electromagnetic **18**, the gas is flowing in a uniform parallel path into the wind tunnel structure **52**.

The coil structures **14**, **16** and **18** may each be provided with three electromagnetic windings along their lengths. The distribution of these windings may be as indicated in FIG. 1 and as described in more detail in the co-pending patent application of Siegfried Hansen cited above. The windings in the electromagnetic structures **14**, **16** and **18** may be energized from three phase electrical signal generator **54**.

As indicated in the foregoing description, a large volume of uniformly accelerated air is supplied to the wind tunnel structure **52** by the three coil structures **14**, **16** and **18**. The amount of air supplied to the wind tunnel is economically accelerated by the indicated structure, principally as a result of the successive gas inputs between the tandem electromagnetic coils. Thus, as briefly mentioned above, an electromagnetic coil tends to act on an ionized plasma only in the region moderately close to the coil. Thus, if a single large coil such as coil **18** were employed, the air toward the center of the coil would not be accelerated to the proper high velocity. Particularly in view of the location of models to be tested in the center of the wind tunnel structure **52**, it is important to have uniform high speed gas across the outlet **12** from the electromagnetic structure. Arrangement of the present invention produces this desired type of output gas flow.

For wind tunnel applications, gas distribution along the acceleration structure is preferably of the form indicated by the plots of FIG. 3. Thus, the pulses of plasma passing down the electromagnetic acceleration structure serve as pistons for entrapped air. This mode of operation is indicated by the central plot of pressure in FIG. 3. Following a short drift space within the wind tunnel structure **52**, gas diffusion tends to level out even the shallow pressure and density fluctuations, both across the wind tunnel, and longitudinally with respect to gas flowing from the accelerator, as indicated in FIG. 3.

As mentioned above, the series of three tandem coils shown in FIG. 4 may be increased in number and each of the coils shortened. With these changes in construction, the variations in pressure are significantly reduced. A conical coil structure may be considered to be in the limiting case of such a change, and is to be preferred, particularly from the standpoint of reduced pressure and density variations.

An embodiment of the invention which includes a flared or conical coil, is shown in FIG. 5. In the arrangement of FIG. 5, a generally conical coil structure **60** is provided in place of the series of coil structures of progressively increasing size, shown in the arrangement of FIG. 4. The structure of FIG. 5 is similar to that of FIG. 4 in that gas is introduced progressively along the length of the acceleration structure. This is accomplished in the structure of FIG. 5 by a gas distribution system including a plenum, or pressure chamber **62** and a porous or perforate shield **64**. Ionizable gas such as air is supplied to the plenum chamber **62** and is then directed both to the apex **66** of the coil structure **60** and through the openings in the shield **64** to pass through the coil structure along its length.

The plenum chamber **62** is made of insulating material to permit ionization of the incoming gas by the encircling electromagnetic coil **68**. The coil **68** is powered by a suitable high frequency power source **69**. Electrostatic pre-ionization structures such as those shown in FIG. 4 could also be used. If they are employed, the plenum chamber would be of metal. Alternatively, the pre-ionization structures may be dispensed with and the high frequency signals supplied to the coil **60** could be relied upon for ionization. As disclosed in D. Curtis et al. application Serial No. 67,645, entitled "Ionization and Plasma Acceleration Apparatus," and filed concurrently with this specification, the power source **70** may be a single phase power supply and may serve to both ionize the gas and to accelerate the resultant plasma. As explained in detail in the Curtis case, the flaring nature of the coil provides an outward component of velocity which accelerates the gas plasma from the mouth **72** of the funnel-shaped structure.

In addition to the components specifically discussed above, the acceleration structure of FIG. 5 includes supporting members **74** and **76** for the shield **64** and coil **60**. The supporting structure **74** may be a series of rods, or the like, to permit the free passage of air to the openings in the shield **64**. An outer housing **78** is also provided to prevent the escape of gas.

The wind tunnel structure **80** is directly connected to the output **72** of the accelerator. As mentioned above, a reasonable drift space is provided between the output **72** of the accelerator and the aerodynamic model **82** under test. This permits a reduction in the variations in gas pressure which may be present as the gas flows from the accelerator. Conventional supporting arrangements **84** and sensing and recording apparatus **86** are provided for mounting the model **82** and for recording its aerodynamic properties. Conventional vacuum pumping apparatus **88** of high capacity is also provided for producing the necessary reduced pressures within the wind tunnel **80**.

It is to be understood that the above-described arrangements are illustrative of the application of the principles of the invention. Numerous other arrangements may be readily devised by those skilled in the art without departing from the spirit and scope of the invention.

Thus, by way of example, but not of limitation, additional electro-magnetic acceleration structures may be provided in the arrangement of FIG. 4 described above and three-phase windings could be employed in the apparatus of FIG. 5. Accordingly, it is to be understood that the present invention is limited only by the spirit and scope of the appended claims.

What is claimed as new is:

1. In a high capacity plasma accelerator, an elongated hollow electromagnetic acceleration structure having an input end of small cross-section and an output end of significantly greater cross-section, means for introducing ionizable material into said structure at the input end of said structure, and means for introducing additional ionizable material into said structure toward the output end thereof.

2. A combination as defined in claim 1 wherein said structure comprises a progressively flared coil, and wherein means are provided for introducing gas along the length of said coil.

3. A combination as defined in claim 1 wherein said structure includes a plurality of discrete electrical coils of progressively increasing diameter, and wherein gas is introduced at the beginning of said smallest coil and between successive coils.

4. In a high capacity plasma accelerator, an elongated electromagnetic acceleration structure having a narrow input cross-section and an increasing cross-section toward the output of said structure, and means for introducing ionizable material into said structure at the reduced input to said structure.

5. In a high capacity plasma accelerator, an elongated hollow electromagnetic acceleration coil structure having an increasing cross-section from its input to its output, means for introducing ionizable material into said structure at the reduced input to said structure, means for supplying high frequency electrical signals to said coil structure, and means for providing subatmospheric pressure conditions within said coil structure.

6. In combination, a wind tunnel, means for mounting an aerodynamic model to be tested in said wind tunnel, vacuum pumping equipment coupled to said tunnel to reduce the pressure in said tunnel, and a plasma acceleration coil structure having a small input cross-section and an output cross-section of significantly greater area, the output of said coil structure being coupled to said wind tunnel.

7. A high capacity plasma accelerator comprising an elongated hollow electromagnetic acceleration coil structure having an increasing cross-section from its input end to its output end, means for introducing ionizable mate-

rial into said structure at the reduced input end of said structure, means for supplying high frequency electrical signals to said coil structure, means for pre-ionizing said ionizable material prior to introduction into said structure, and means for providing subatmospheric pressure conditions within said coil structure.

8. In combination, a wind tunnel, means for mounting an aerodynamic model to be tested in said wind tunnel, vacuum pumping equipment coupled to said tunnel to reduce the pressure in said tunnel, a plasma acceleration coil structure having a small input cross-sectional area and an output end having a cross-section of significantly greater area, the output of said coil structure being coupled to said wind tunnel, and means for supplying ionizable material to said coil structure at its small input end and at another point along the length of said coil structure.

9. A combination as defined in claim 8 wherein said coil structure is a progressively flared coil.

10. A combination as defined in claim 8 wherein said means for supplying ionizable material constitutes an air distribution system.

11. In combination, a channel, vacuum pumping equipment coupled to said channel to reduce its pressure, a plurality of discrete plasma acceleration coil structures, means for supplying ionizable material to each of said coil structures at the input ends thereof, and means for combining the accelerated plasmas from the output ends of each of said accelerator structures and applying them to said channel.

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