

Liquid cooling is advantageous because it is efficient. Water cooling is particularly desirable because water has high heat capacity, and it is both safe to handle and environmentally benign. Also, chilled water is readily available in nearly all manufacturing, university and research and development facilities. A barrier to using water for cooling microwave plasma discharge tubes is that water also readily absorbs microwave energy. Similarly, many other desirable cooling liquids readily absorb microwave energy.

Certain fluids such as silicone oils, some chlorofluorocarbons, and various hydrocarbon compounds do not absorb microwave energy and thus can be used to cool the outside of a plasma discharge tube. Unfortunately, these fluids are often environmentally undesirable, hazardous to handle, and expensive. In addition, using these fluids requires the use of closed-loop heat exchangers, which further increases the cost and complexity of the system.

A number of techniques have been used to generate plasmas and to produce activated gases. These include capacitively coupled discharges, inductively coupled discharges and microwave discharges. None of the prior devices have been adequate for producing high-flow-rate, contamination-free, chemically activated gases useful for industrial applications.

SUMMARY

In a first aspect, there is provided an apparatus for generating plasma, including a plasma discharge tube substantially transparent to microwave energy, the plasma discharge tube having a longitudinal axis; a conductive coil wound around an outer surface of the plasma discharge tube, the conductive coil including an electrically conductive material; a microwave cavity surrounding the plasma discharge tube; a waveguide coupled to the microwave cavity for guiding the microwave energy into the plasma discharge tube such that the plasma is generated in the plasma discharge tube, the waveguide having a rectangular cross-section defining a narrower side of the rectangular cross-section and a wider side of the rectangular cross-section, a first cross-sectional axis of the rectangular cross-section being parallel to the wider side of the rectangular cross-section and a second cross-sectional axis of the rectangular cross-section being parallel to the narrower side of the rectangular cross-section, the second cross-sectional axis being positioned at a predetermined angle with respect to the longitudinal axis of the plasma discharge tube such that an electric field of the

microwave energy induces an electric current in the conductive coil, the electric current affecting power absorption in the plasma discharge tube, the predetermined angle being selectable such that power absorption in the plasma discharge tube is according to a predetermined profile with respect to the longitudinal axis of the plasma discharge tube; and
5 an actuator for receiving a signal to control the predetermined angle.

In a second aspect, there is provided an apparatus for generating plasma, including: a plasma discharge tube substantially transparent to microwave energy, the plasma discharge tube having a longitudinal axis; a conductive coil wound around an outer surface of the plasma discharge tube, the conductive coil including an electrically conductive material, an
10 electric field of the microwave energy inducing an electric current in the conductive coil, the electric current affecting power absorption in the plasma discharge tube; a microwave cavity surrounding the plasma discharge tube; a waveguide coupled to the microwave cavity for guiding the microwave energy into the plasma discharge tube such that the plasma is generated in the plasma discharge tube, the waveguide having a rectangular cross-section
15 defining a narrower side of the rectangular cross-section and a wider side of the rectangular cross-section, a first cross-sectional axis of the rectangular cross-section being parallel to the wider side of the rectangular cross-section and a second cross-sectional axis of the rectangular cross-section being parallel to the narrower side of the rectangular cross-section; a rotational coupling device for coupling the waveguide to the plasma discharge tube, the rotational
20 coupling device allowing the waveguide to be rotated with respect to the plasma discharge tube about an axis which is parallel to a longitudinal axis of the waveguide to adjust an angle between the second cross-sectional axis of the waveguide and the longitudinal axis of the plasma discharge tube, such that power absorption in the plasma discharge tube is adjustable via the rotational coupling device to a predetermined profile with respect to the longitudinal
25 axis of the plasma discharge tube; and an actuator for receiving a signal to adjust the angle between the second cross-sectional axis and the longitudinal axis of the plasma discharge tube.

In a third aspect, there is provided an apparatus for generating plasma, including: a plasma discharge tube substantially transparent to microwave energy, the plasma discharge
30 tube having a longitudinal axis; a conductive coil wound around an outer surface of the plasma discharge tube, the conductive coil including an electrically conductive material; a

microwave cavity surrounding the plasma discharge tube, and a waveguide coupled to the microwave cavity for guiding the microwave energy into the plasma discharge tube such that the plasma is generated in the plasma discharge tube, the waveguide having a rectangular cross-section defining a narrower side of the rectangular cross-section and a wider side of the rectangular cross-section, a first cross-sectional axis of the rectangular cross-section being parallel to the wider side of the rectangular cross-section and a second cross-sectional axis of the rectangular cross-section being parallel to the narrower side of the rectangular cross-section, the second cross-sectional axis being positioned at a predetermined angle with respect to the longitudinal axis of the plasma discharge tube such that an electric field of the microwave energy induces an electric current in the conductive coil, the electric current affecting power absorption in the plasma discharge tube, the predetermined angle being selectable such that power absorption in the plasma discharge tube is according to a predetermined profile with respect to the longitudinal axis of the plasma discharge tube, wherein the predetermined angle is between 30° and 90°.

In a fourth aspect, there is provided an apparatus for generating plasma, including: a plasma discharge tube substantially transparent to microwave energy, the plasma discharge tube having a longitudinal axis; a conductive coil wound around an outer surface of the plasma discharge tube, the conductive coil including an electrically conductive material, an electric field of the microwave energy inducing an electric current in the conductive coil, the electric current affecting power absorption in the plasma discharge tube; a microwave cavity surrounding the plasma discharge tube; a waveguide coupled to the microwave cavity for guiding the microwave energy into the plasma discharge tube such that the plasma is generated in the plasma discharge tube, the waveguide having a rectangular cross-section defining a narrower side of the rectangular cross-section and a wider side of the rectangular cross-section, a first cross-sectional axis of the rectangular cross-section being parallel to the wider side of the rectangular cross-section and a second cross-sectional axis of the rectangular cross-section being parallel to the narrower side of the rectangular cross-section; and a rotational coupling device for coupling the waveguide to the plasma discharge tube, the rotational coupling device allowing the waveguide to be rotated with respect to the plasma discharge tube about an axis which is parallel to a longitudinal axis of the waveguide to adjust an angle between the second cross-sectional axis of the waveguide and the longitudinal axis

of the plasma discharge tube, such that power absorption in the plasma discharge tube is adjustable via the rotational coupling device to a predetermined profile with respect to the longitudinal axis of the plasma discharge tube.

According to an example, an apparatus for generating plasma is provided. The apparatus includes a plasma discharge tube being substantially transparent to microwave energy and having a longitudinal axis. A conductive coil comprising an electrically conductive material is substantially helically wound around an outer surface of the plasma discharge tube. A microwave cavity surrounds the plasma discharge tube. A waveguide is coupled to the microwave cavity for guiding the microwave energy into the plasma discharge tube such that the plasma is generated in the plasma discharge tube. The waveguide has a major cross-sectional axis and a minor cross-sectional axis, the major and minor cross-sectional axes being positioned with respect to the longitudinal axis of the plasma discharge tube such that an electric field of the microwave energy is oriented at a predetermined angle with respect to the longitudinal axis of the plasma discharge tube. The electric field of the microwave energy induces an electric current in the conductive coil, the electric current affecting power absorption in the plasma discharge tube, the predetermined angle being selectable such that power absorption in the plasma discharge tube is according to a predetermined profile with respect to the longitudinal axis of the plasma discharge tube.

According to an example, the predetermined angle is such that the electric field is oriented substantially perpendicular to the longitudinal axis of the plasma discharge tube. In some exemplary embodiments, the predetermined angle is such that the electric field is oriented at an angle of 30° to 90° with respect to the longitudinal axis of the plasma discharge tube. In some exemplary embodiments, the predetermined angle is such that the electric field is oriented at an angle of 45° to 90° with respect to the longitudinal axis of the plasma discharge tube. In some exemplary embodiments, the predetermined angle is selected to increase uniformity of power absorption with respect to the longitudinal axis of the plasma discharge tube.

According to an example, the conductive coil comprises a plurality of loops around the plasma discharge tube, the plurality of loops defining a pattern of spacing between adjacent loops, the pattern of spacing being selectable based on a predetermined desired effect of the current induced in the conductive coil on the power absorption in the plasma discharge

tube. In some exemplary embodiments, the pattern of spacing between adjacent loops is selected to increase uniformity of power absorption with respect to the longitudinal axis of the plasma discharge tube. In some exemplary embodiments, the spacing between selected adjacent loops can be decreased to increase the electric current induced in the conductive coil such that propagation of microwave energy in the plasma discharge tube in proximity to the selected adjacent loops increases. In some exemplary embodiments, the spacing between selected adjacent loops can be increased to decrease the electric current induced in the conductive coil such that propagation of microwave energy in the plasma discharge tube in proximity to the selected adjacent loops decreases.

According to an example, the conductive coil is thermally coupled to the plasma discharge tube, and the conductive coil comprises a channel through which a cooling fluid can flow, such that the cooling fluid removes heat from the plasma discharge tube. The spacing between adjacent loops can be selected to control temperature of the plasma discharge tube.

According to an example, the apparatus further comprises a microwave choke at each of two ends of the conductive coil, the microwave chokes substantially preventing leakage of the microwave energy from the plasma discharge tube.

According to an example, the conductive coil is helically wound around the outer surface of the plasma discharge tube.

According to an example, a controller controls the predetermined angle between the electric field of the microwave energy and the longitudinal axis of the plasma discharge tube. The apparatus can include at least one of an electromagnetic field sensor for generating a first signal indicative of electromagnetic field intensity in the plasma discharge tube and a temperature sensor for generating a second signal indicative of temperature in the plasma discharge tube, and the controller controls the predetermined angle based on at least one of the first and second signals. The apparatus can include at least one actuator for rotating the waveguide with respect to the plasma discharge tube to adjust the predetermined angle, the controller controlling the at least one actuator to control the predetermined angle.

According to an example, an apparatus for generating plasma is provided. The apparatus includes a plasma discharge tube being substantially transparent to microwave energy and having a longitudinal axis. A conductive coil comprising an electrically conductive material is substantially helically wound around an outer surface of the plasma

discharge tube. An electric field of the microwave energy induces an electric current in the conductive coil, and the electric current affects power absorption in the plasma discharge tube. A microwave cavity surrounds the plasma discharge tube. A waveguide is coupled to the microwave cavity for guiding the microwave energy into the plasma discharge tube such that the plasma is generated in the plasma discharge tube. A rotational coupling device couples the waveguide to the plasma discharge tube and allows the waveguide to be rotated with respect to the plasma discharge tube to adjust an angle between the electric field of the microwave energy and the longitudinal axis of the plasma discharge tube, such that power absorption in the plasma discharge tube is adjustable via the rotational coupling device to a predetermined profile with respect to the longitudinal axis of the plasma discharge tube.

According to an example, the waveguide comprises a major cross-sectional axis and a minor cross-sectional axis, the rotational coupling device allowing the major and minor cross-sectional axes to be adjusted with respect to the longitudinal axis of the plasma discharge tube to adjust the angle between the electric field of the microwave energy and the longitudinal axis of the plasma discharge tube.

According to an example, the apparatus further comprises a controller for adjusting the angle between the electric field of the microwave energy and the longitudinal axis of the plasma discharge tube. The apparatus can include at least one of an electromagnetic field sensor for generating a first signal indicative of electromagnetic field intensity in the plasma discharge tube and a temperature sensor for generating a second signal indicative of temperature in the plasma discharge tube, and the controller controls the angle between the electric field of the microwave energy and the longitudinal axis of the plasma discharge tube based on at least one of the first and second signals. The apparatus can include at least one actuator for rotating the waveguide with respect to the plasma discharge tube to adjust the angle between the electric field of the microwave energy and the longitudinal axis of the plasma discharge tube, the controller controlling the at least one actuator to control the angle between the electric field of the microwave energy and the longitudinal axis of the plasma discharge tube.

According to an example, the angle between the electric field of the microwave energy and the longitudinal axis of the plasma discharge tube is adjustable from 30° to 90°. In some exemplary embodiments, the angle between the electric field of the microwave energy and the

longitudinal axis of the plasma discharge tube is adjustable from 45° to 90°. In some exemplary embodiments, the angle between the electric field of the microwave energy and the longitudinal axis of the plasma discharge tube is adjusted to increase uniformity of power absorption with respect to the longitudinal axis of the plasma discharge tube.

5 According to an example, the apparatus further comprises a sensor for monitoring axial uniformity of the plasma in the plasma discharge tube.

 According to an example, the conductive coil comprises a plurality of loops around the plasma discharge tube, the plurality of loops defining a pattern of spacing between adjacent loops, the pattern of spacing being selectable based on a predetermined desired effect
10 of the current induced in the conductive coil on the power absorption in the plasma discharge tube. In some exemplary embodiments, the pattern of spacing between adjacent loops is selected to increase uniformity of power absorption with respect to the longitudinal axis of the plasma discharge tube. In some exemplary embodiments, the spacing between selected adjacent loops can be decreased to increase the electric current induced in the conductive coil
15 such that propagation of microwave energy in the plasma discharge tube in proximity to the selected adjacent loops increases. In some exemplary embodiments, the spacing between selected adjacent loops can be increased to decrease the electric current induced in the conductive coil such that propagation of microwave energy in the plasma discharge tube in proximity to the selected adjacent loops decreases.

20 According to an example, the conductive coil is thermally coupled to the plasma discharge tube, and the conductive coil comprises a channel through which a cooling fluid can flow, such that the cooling fluid removes heat from the plasma discharge tube. The spacing between adjacent loops can be selected to minimize the temperature of the plasma discharge tube while ensuring propagation of the microwave fields.

25 According to an example, the apparatus further comprises a microwave choke at each of two ends of the conductive coil, the microwave chokes substantially preventing leakage of the microwave energy from the plasma discharge tube.

 According to an example, the conductive coil is helically wound around the outer surface of the plasma discharge tube.

30 According to an example, a plasma discharge tube assembly for a plasma generating device is provided. The assembly includes a plasma discharge tube being substantially

transparent to microwave energy and having a longitudinal axis. A conductive coil comprising an electrically conductive material is substantially helically wound around an outer surface of the plasma discharge tube. An electric field of the microwave energy induces an electric current in the conductive coil, the electric current affecting power absorption in the plasma discharge tube. A plurality of microwave chokes is disposed at each of two ends of the conductive coil, the microwave chokes substantially preventing leakage of the microwave energy from the plasma discharge tube.

According to an example, the conductive coil comprises a plurality of loops around the plasma discharge tube, the plurality of loops defining a pattern of spacing between adjacent loops, the pattern of spacing being selectable based on a predetermined desired effect of the current induced in the conductive coil on the power absorption in the plasma discharge tube. In some exemplary embodiments, the pattern of spacing between adjacent loops is selected to increase uniformity of power absorption with respect to the longitudinal axis of the plasma discharge tube. In some exemplary embodiments, the spacing between selected adjacent loops can be decreased to increase the electric current induced in the conductive coil such that propagation of microwave energy in the plasma discharge tube in proximity to the selected adjacent loops increases. In some exemplary embodiments, the spacing between selected adjacent loops can be increased to decrease the electric current induced in the conductive coil such that propagation of microwave energy in the plasma discharge tube in proximity to the selected adjacent loops decreases. In some exemplary embodiments, the spacing between adjacent loops is between 0.2 and 1 cm.

According to an example, the conductive coil is thermally coupled to the plasma discharge tube, and the conductive coil comprises a channel through which a cooling fluid can flow, such that the cooling fluid removes heat from the plasma discharge tube.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other features and advantages will be apparent from the more particular description of preferred embodiments, as illustrated in the accompanying drawings, in which like reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the inventive concept.

FIG. 1 includes a schematic cross-sectional view of a liquid-cooled microwave plasma applicator.

FIG. 2 includes a schematic cross-sectional view of a liquid-cooled microwave plasma applicator, which can use microwave-absorbing fluids.

5 FIG. 3 includes a schematic cross-sectional diagram of an embodiment of the cooling jacket illustrated in FIG. 2.

FIGs. 4A and 4B include schematic power absorption profiles for the plasma applicator 2 illustrated in FIG. 2.

10 FIGs. 5A through 5D include schematic diagrams which illustrate a plasma applicator, according to some exemplary embodiments.

1. An apparatus for generating plasma, comprising:
 - a plasma discharge tube substantially transparent to microwave energy, the plasma discharge tube having a longitudinal axis;
 - a conductive coil wound around an outer surface of the plasma discharge tube, the conductive coil comprising an electrically conductive material;
 - a microwave cavity surrounding the plasma discharge tube;
 - a waveguide coupled to the microwave cavity for guiding the microwave energy into the plasma discharge tube such that the plasma is generated in the plasma discharge tube, the waveguide having a rectangular cross-section defining a narrower side of the rectangular cross-section and a wider side of the rectangular cross-section, a first cross-sectional axis of the rectangular cross-section being parallel to the wider side of the rectangular cross-section and a second cross-sectional axis of the rectangular cross-section being parallel to the narrower side of the rectangular cross-section, the second cross-sectional axis being positioned at a predetermined angle with respect to the longitudinal axis of the plasma discharge tube such that an electric field of the microwave energy induces an electric current in the conductive coil, the electric current affecting power absorption in the plasma discharge tube, the predetermined angle being selectable such that power absorption in the plasma discharge tube is according to a predetermined profile with respect to the longitudinal axis of the plasma discharge tube; and
 - an actuator for receiving a signal to control the predetermined angle.
2. The apparatus of claim 1, wherein the predetermined angle is such that the second cross-sectional axis is oriented substantially perpendicular to the longitudinal axis of the plasma discharge tube.
3. The apparatus of claim 1, wherein the predetermined angle is such that the second cross-sectional axis is oriented at an angle of 30° to 90° with respect to the longitudinal axis of the plasma discharge tube.
4. The apparatus of claim 1, wherein the predetermined angle is such that the second cross-sectional axis is oriented at an angle of 45° to 90° with respect to the longitudinal axis of the plasma discharge tube.
5. The apparatus of claim 1, wherein the predetermined angle is selected to increase uniformity of power absorption with respect to the longitudinal axis of the plasma discharge tube.

6. The apparatus of claim 1, wherein the conductive coil comprises a plurality of loops around the plasma discharge tube, the plurality of loops defining a pattern of spacing between adjacent loops, the pattern of spacing being selectable based on a predetermined desired effect of the current induced in the conductive coil on the power absorption in the plasma discharge tube.
7. The apparatus of claim 6, wherein the pattern of spacing between adjacent loops is selected to increase uniformity of power absorption with respect to the longitudinal axis of the plasma discharge tube.
8. The apparatus of claim 6, wherein the spacing between selected adjacent loops can be decreased to increase the electric current induced in the conductive coil such that propagation of microwave energy in the plasma discharge tube in proximity to the selected adjacent loops increases.
9. The apparatus of claim 6, wherein the spacing between selected adjacent loops can be increased to decrease the electric current induced in the conductive coil such that propagation of microwave energy in the plasma discharge tube in proximity to the selected adjacent loops decreases.
10. The apparatus of claim 1, wherein:
 - the conductive coil is thermally coupled to the plasma discharge tube;
 - the conductive coil comprises a channel through which a cooling fluid can flow, such that the cooling fluid removes heat from the plasma discharge tube.
11. The apparatus of claim 1, further comprising a microwave choke at each of two ends of the conductive coil, the microwave chokes substantially preventing leakage of the microwave energy from the plasma discharge tube.
12. The apparatus of claim 1, wherein the conductive coil is helically wound around the outer surface of the plasma discharge tube.
13. The apparatus of claim 1, further comprising at least one of an electromagnetic field sensor for generating a first signal indicative of electromagnetic field intensity in the plasma discharge tube

or a temperature sensor for generating a second signal indicative of temperature in the plasma discharge tube, the controller controlling the predetermined angle based on at least one of the first and second signals.

14. The apparatus of claim 1, wherein the actuator rotates the waveguide with respect to the plasma discharge tube about an axis which is parallel to a longitudinal axis of the waveguide to adjust the predetermined angle, a controller controlling the actuator to control the predetermined angle.

15. An apparatus for generating plasma, comprising:

- a plasma discharge tube substantially transparent to microwave energy, the plasma discharge tube having a longitudinal axis;

- a conductive coil wound around an outer surface of the plasma discharge tube, the conductive coil comprising an electrically conductive material, an electric field of the microwave energy inducing an electric current in the conductive coil, the electric current affecting power absorption in the plasma discharge tube;

- a microwave cavity surrounding the plasma discharge tube;

- a waveguide coupled to the microwave cavity for guiding the microwave energy into the plasma discharge tube such that the plasma is generated in the plasma discharge tube, the waveguide having a rectangular cross-section defining a narrower side of the rectangular cross-section and a wider side of the rectangular cross-section, a first cross-sectional axis of the rectangular cross-section being parallel to the wider side of the rectangular cross-section and a second cross-sectional axis of the rectangular cross-section being parallel to the narrower side of the rectangular cross-section;

- a rotational coupling device for coupling the waveguide to the plasma discharge tube, the rotational coupling device allowing the waveguide to be rotated with respect to the plasma discharge tube about an axis which is parallel to a longitudinal axis of the waveguide to adjust an angle between the second cross-sectional axis of the waveguide and the longitudinal axis of the plasma discharge tube, such that power absorption in the plasma discharge tube is adjustable via the rotational coupling device to a predetermined profile with respect to the longitudinal axis of the plasma discharge tube; and

- an actuator for receiving a signal to adjust the angle between the second cross-sectional axis and the longitudinal axis of the plasma discharge tube.

16. The apparatus of claim 15, further comprising at least one of an electromagnetic field sensor for generating a first signal indicative of electromagnetic field intensity in the plasma discharge tube or a temperature sensor for generating a second signal indicative of temperature in the plasma discharge tube, the actuator controlling the angle between the second cross-sectional axis and the longitudinal axis of the plasma discharge tube based on at least one of the first and second signals.
17. The apparatus of claim 15, wherein the actuator rotates the waveguide with respect to the plasma discharge tube to adjust the angle between the second cross-sectional axis and the longitudinal axis of the plasma discharge tube, a controller controlling the actuator to control the angle between the second cross-sectional axis of the waveguide and the longitudinal axis of the plasma discharge tube.
18. The apparatus of claim 15, wherein the angle between the second cross-sectional axis and the longitudinal axis of the plasma discharge tube is adjustable from 30° to 90°.
19. The apparatus of claim 15, wherein the angle between the second cross-sectional axis and the longitudinal axis of the plasma discharge tube is adjustable from 45° to 90°.
20. The apparatus of claim 15, wherein the angle between the second cross-sectional axis and the longitudinal axis of the plasma discharge tube is adjusted to increase uniformity of power absorption with respect to the longitudinal axis of the plasma discharge tube.
21. The apparatus of claim 15, further comprising a sensor for monitoring axial uniformity of the plasma in the plasma discharge tube.
22. The apparatus of claim 15, wherein the conductive coil comprises a plurality of loops around the plasma discharge tube, the plurality of loops defining a pattern of spacing between adjacent loops, the pattern of spacing being selectable based on a predetermined desired effect of the current induced in the conductive coil on the power absorption in the plasma discharge tube.
23. The apparatus of claim 22, wherein the pattern of spacing between adjacent loops is selected to increase uniformity of power absorption with respect to the longitudinal axis of the plasma discharge tube.

24. The apparatus of claim 22, wherein the spacing between selected adjacent loops can be decreased to increase the electric current induced in the conductive coil such that propagation of microwave energy in the plasma discharge tube in proximity to the selected adjacent loops increases.
25. The apparatus of claim 22, wherein the spacing between selected adjacent loops can be increased to decrease the electric current induced in the conductive coil such that propagation of microwave energy in the plasma discharge tube in proximity to the selected adjacent loops decreases.
26. The apparatus of claim 15, wherein:
the conductive coil is thermally coupled to the plasma discharge tube;
the conductive coil comprises a channel through which a cooling fluid can flow, such that the cooling fluid removes heat from the plasma discharge tube.
27. The apparatus of claim 15, further comprising a microwave choke at each of two ends of the conductive coil, the microwave chokes substantially preventing leakage of the microwave energy from the plasma discharge tube.
28. The apparatus of claim 15, wherein the conductive coil is helically wound around the outer surface of the plasma discharge tube.
29. An apparatus for generating plasma, comprising:
a plasma discharge tube substantially transparent to microwave energy, the plasma discharge tube having a longitudinal axis;
a conductive coil wound around an outer surface of the plasma discharge tube, the conductive coil comprising an electrically conductive material;
a microwave cavity surrounding the plasma discharge tube, and
a waveguide coupled to the microwave cavity for guiding the microwave energy into the plasma discharge tube such that the plasma is generated in the plasma discharge tube, the waveguide having a rectangular cross-section defining a narrower side of the rectangular cross-section and a wider side of the rectangular cross-section, a first cross-sectional axis of the rectangular cross-section being parallel to the wider side of the rectangular cross-section and a second cross-sectional axis of the rectangular cross-section being parallel to the narrower side of the

rectangular cross-section, the second cross-sectional axis being positioned at a predetermined angle with respect to the longitudinal axis of the plasma discharge tube such that an electric field of the microwave energy induces an electric current in the conductive coil, the electric current affecting power absorption in the plasma discharge tube, the predetermined angle being selectable such that power absorption in the plasma discharge tube is according to a predetermined profile with respect to the longitudinal axis of the plasma discharge tube, wherein the predetermined angle is between 30° and 90°.

30. The apparatus of claim 29, wherein the predetermined angle is such that the second cross-sectional axis is oriented substantially perpendicular to the longitudinal axis of the plasma discharge tube.

31. The apparatus of claim 29, wherein the predetermined angle is such that the second cross-sectional axis is oriented at an angle of 45° to 90° with respect to the longitudinal axis of the plasma discharge tube.

32. The apparatus of claim 29, wherein the predetermined angle is selected to increase uniformity of power absorption with respect to the longitudinal axis of the plasma discharge tube.

33. The apparatus of claim 29, wherein the conductive coil comprises a plurality of loops around the plasma discharge tube, the plurality of loops defining a pattern of spacing between adjacent loops, the pattern of spacing being selectable based on a predetermined desired effect of the current induced in the conductive coil on the power absorption in the plasma discharge tube.

34. The apparatus of claim 33, wherein the pattern of spacing between adjacent loops is selected to increase uniformity of power absorption with respect to the longitudinal axis of the plasma discharge tube.

35. The apparatus of claim 33, wherein the spacing between selected adjacent loops can be decreased to increase the electric current induced in the conductive coil such that propagation of microwave energy in the plasma discharge tube in proximity to the selected adjacent loops increases.

36. The apparatus of claim 33, wherein the spacing between selected adjacent loops can be increased to decrease the electric current induced in the conductive coil such that propagation of microwave energy in the plasma discharge tube in proximity to the selected adjacent loops decreases.

37. The apparatus of claim 29, wherein:

the conductive coil is thermally coupled to the plasma discharge tube;

the conductive coil comprises a channel through which a cooling fluid can flow, such that the cooling fluid removes heat from the plasma discharge tube.

38. The apparatus of claim 29, further comprising a microwave choke at each of two ends of the conductive coil, the microwave chokes substantially preventing leakage of the microwave energy from the plasma discharge tube.

39. The apparatus of claim 29, wherein the conductive coil is helically wound around the outer surface of the plasma discharge tube.

40. An apparatus for generating plasma, comprising:

a plasma discharge tube substantially transparent to microwave energy, the plasma discharge tube having a longitudinal axis;

a conductive coil wound around an outer surface of the plasma discharge tube, the conductive coil comprising an electrically conductive material, an electric field of the microwave energy inducing an electric current in the conductive coil, the electric current affecting power absorption in the plasma discharge tube;

a microwave cavity surrounding the plasma discharge tube;

a waveguide coupled to the microwave cavity for guiding the microwave energy into the plasma discharge tube such that the plasma is generated in the plasma discharge tube, the waveguide having a rectangular cross-section defining a narrower side of the rectangular cross-section and a wider side of the rectangular cross-section, a first cross-sectional axis of the rectangular cross-section being parallel to the wider side of the rectangular cross-section and a second cross-sectional axis of the rectangular cross-section being parallel to the narrower side of the rectangular cross-section; and

a rotational coupling device for coupling the waveguide to the plasma discharge tube, the rotational coupling device allowing the waveguide to be rotated with respect to the plasma

discharge tube about an axis which is parallel to a longitudinal axis of the waveguide to adjust an angle between the second cross-sectional axis of the waveguide and the longitudinal axis of the plasma discharge tube, such that power absorption in the plasma discharge tube is adjustable via the rotational coupling device to a predetermined profile with respect to the longitudinal axis of the plasma discharge tube.

41. The apparatus of claim 40, wherein the angle between the second cross-sectional axis and the longitudinal axis of the plasma discharge tube is adjustable from 30° to 90°.

42. The apparatus of claim 40, wherein the angle between the second cross-sectional axis and the longitudinal axis of the plasma discharge tube is adjustable from 45° to 90°.

43. The apparatus of claim 40, wherein the angle between the second cross-sectional axis and the longitudinal axis of the plasma discharge tube is adjusted to increase uniformity of power absorption with respect to the longitudinal axis of the plasma discharge tube.

44. The apparatus of claim 40, further comprising a sensor for monitoring axial uniformity of the plasma in the plasma discharge tube.

45. The apparatus of claim 40, wherein the conductive coil comprises a plurality of loops around the plasma discharge tube, the plurality of loops defining a pattern of spacing between adjacent loops, the pattern of spacing being selectable based on a predetermined desired effect of the current induced in the conductive coil on the power absorption in the plasma discharge tube.

46. The apparatus of claim 45, wherein the pattern of spacing between adjacent loops is selected to increase uniformity of power absorption with respect to the longitudinal axis of the plasma discharge tube.

47. The apparatus of claim 45, wherein the spacing between selected adjacent loops can be decreased to increase the electric current induced in the conductive coil such that propagation of microwave energy in the plasma discharge tube in proximity to the selected adjacent loops increases.

48. The apparatus of claim 45, wherein the spacing between selected adjacent loops can be increased to decrease the electric current induced in the conductive coil such that propagation of microwave energy in the plasma discharge tube in proximity to the selected adjacent loops decreases.
49. The apparatus of claim 40, wherein:
the conductive coil is thermally coupled to the plasma discharge tube;
the conductive coil comprises a channel through which a cooling fluid can flow, such that the cooling fluid removes heat from the plasma discharge tube.
50. The apparatus of claim 40, further comprising a microwave choke at each of two ends of the conductive coil, the microwave chokes substantially preventing leakage of the microwave energy from the plasma discharge tube.
51. The apparatus of claim 40, wherein the conductive coil is helically wound around the outer surface of the plasma discharge tube.