



(19) **United States**

(12) **Patent Application Publication**  
Matsumoto et al.

(10) **Pub. No.: US 2002/0060527 A1**  
(43) **Pub. Date: May 23, 2002**

(54) **MICROWAVE/D.C. CYCLOTRON WAVE  
CONVERTER HAVING DECREASED  
MAGNETIC FIELD**

(52) **U.S. Cl. .... 315/291**

(75) **Inventors: Hiroshi Matsumoto, Kyoto-shi (JP);  
Vladimir A. Vanke, Kyoto-shi (JP);  
Naoki Shinohara, Kyoto-shi (JP)**

(57) **ABSTRACT**

Correspondence Address:  
**OLIFF & BERRIDGE, PLC**  
**P.O. BOX 19928**  
**ALEXANDRIA, VA 22320 (US)**

A microwave/DC converter employing fast cyclotron wave of the electron beam. Coupling section for feeding energy into the electron beam contains two microwave cavities **3, 7**. The second cavity **7** has a quadrupole electric field, receives the electron beam already slightly modulated by the first cavity **3**, which is a resonant coupler with uniform transverse electric field and operates at a half of the second resonant cavity frequency. For the effective interaction in both cavities **3, 7** uniform static magnetic field corresponds to the cyclotron frequency equal to a half of external microwave power source frequency. Asymmetrically reversed magnetic field is used between microwave cavities and collector to achieve the maximal efficiency of the microwave energy conversion into DC energy. Additional electrode **9** of the collector **11** creates a potential distribution providing converter with an effective protection against secondary emission influence. Application to the design of high-power and high efficient microwave/DC power converters for operation in the centimeter and millimeter wavebands is shown.

(73) **Assignee: Kansai Technology licensing Organiza-  
tion Co., Ltd., Kyoto-shi (JP)**

(21) **Appl. No.: 09/902,668**

(22) **Filed: Jul. 12, 2001**

(30) **Foreign Application Priority Data**

Nov. 22, 2000 (JP) ..... 2000-355358

**Publication Classification**

(51) **Int. Cl.<sup>7</sup> ..... G05F 1/00**

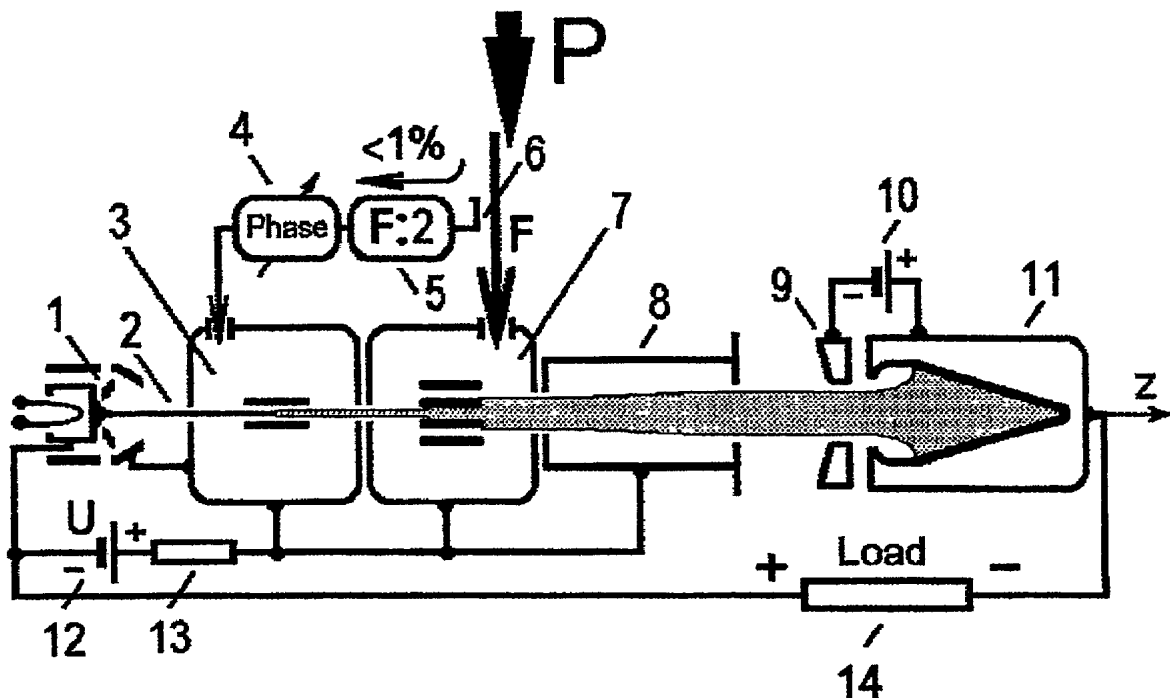


Fig. 1A

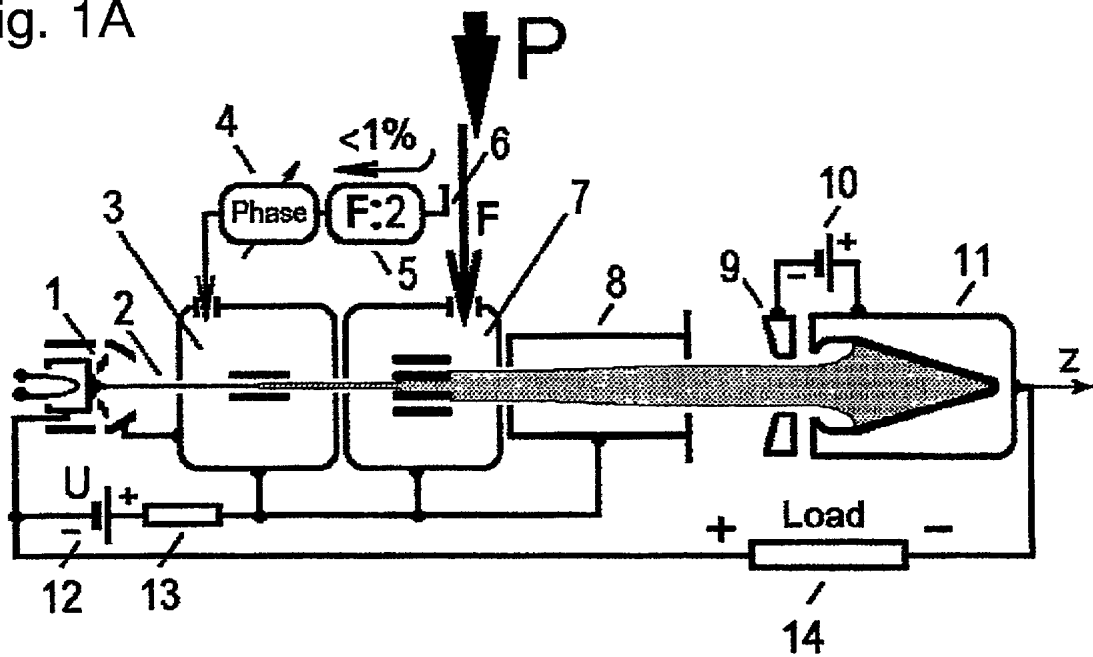


Fig. 1B

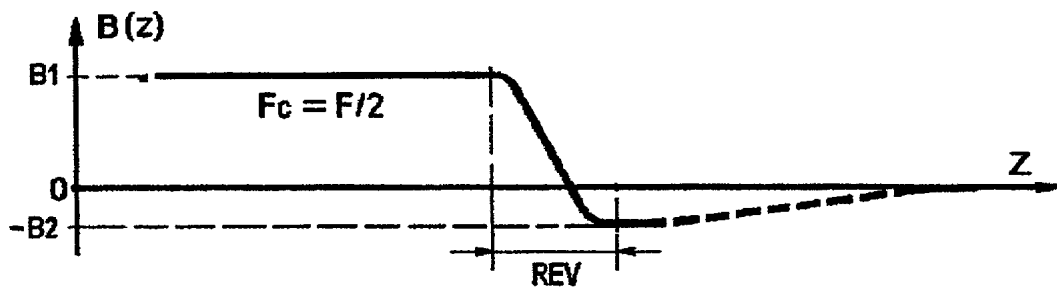


Fig. 2

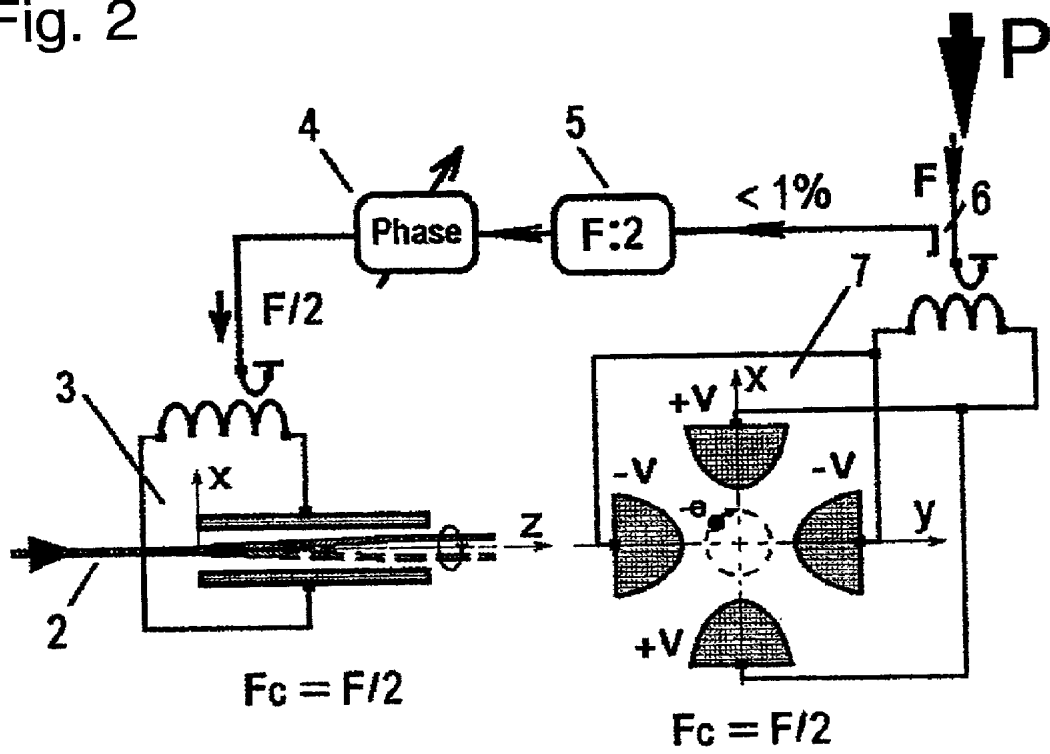


Fig. 3A

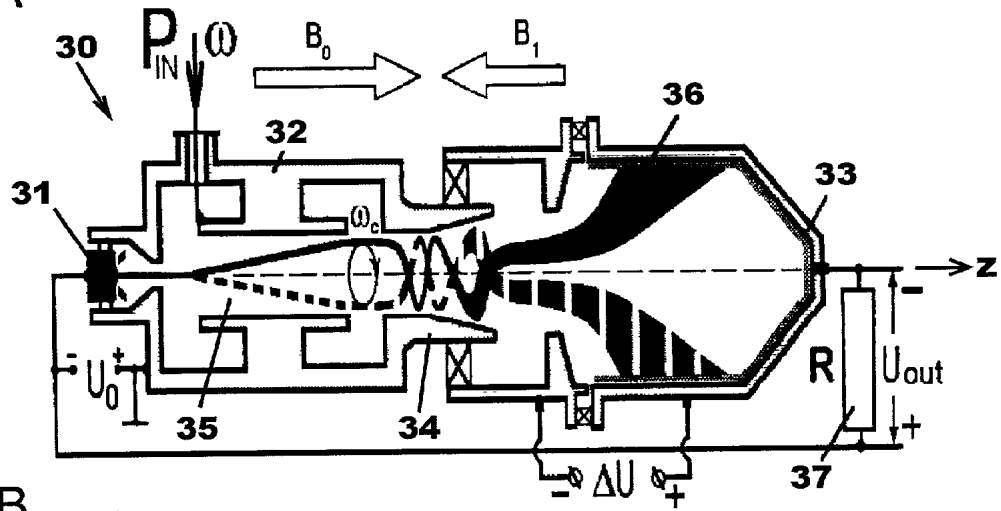
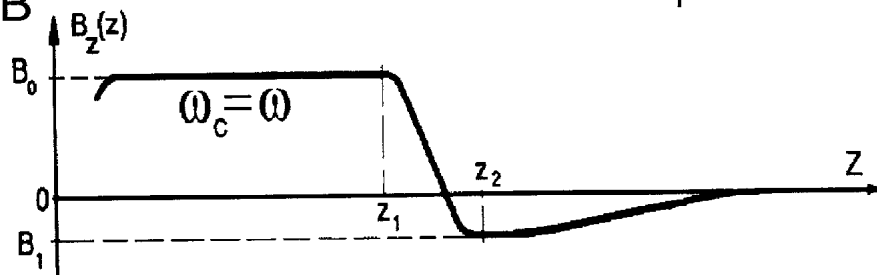


Fig. 3B



### MICROWAVE/D.C. CYCLOTRON WAVE CONVERTER HAVING DECREASED MAGNETIC FIELD

[0001] The present invention relates to microwave/Direct Current (DC) power converters employing fast cyclotron wave of the electron beam. The microwave/DC power converters may be used as a receiver in a microwave energy transmission (MET) system or a wireless power transmission (WPT) system.

#### BACKGROUND OF THE INVENTION

[0002] In connection with successful developing ideas of WPT during the last several decades, there appeared a new problem, namely, the problem of back conversion of high power microwave energy into the energy of direct current (DC). It is not impossible that in future microwave technology will find its wide scale application in this field.

[0003] Well-known rectennas (rectifying antennas) with Schottky-diodes have played and play a fundamental role at the stage of principal demonstration of the possibilities of highly efficient wireless power transmission by microwaves. However, they become not so attractive for future real high power industrial WPT systems, because of some essential problems as:

- [0004] low power level of single rectenna element;
- [0005] low output voltage and therefore, necessity to connect diodes in series; and
- [0006] high level of breakdown possibility being dangerous even at rather small levels of microwave or DC overloads.

[0007] Industrial energy systems always demand and use high power and high voltage devices to decrease losses and to increase reliability.

[0008] The most studied cyclotron wave converter (CWC) is shown in **FIG. 3A** (Vladimir A. Vanke et al., "Cyclotron Wave Converter of Microwaves into DC", IEICE Trans. on Electronics (Japan), Vol. E81-C (1998), No. 7 (July), p.1136). The CWC **30** comprises an electron gun **31**, a microwave cavity **32**, a collector **33** and a transition space **34** aligned on the z-axis. The microwave cavity **32** includes a space of interaction **35** usually called "Cuccia coupler" which is subjected to a static magnetic field  $B_0$  in the direction of z created by an external magnetic field generator (not shown). The transition space **34** is subjected to another external static magnetic field  $B_1$  in the direction of -z. The z component of the magnetic flux density  $z_0$  on the z-axis due to the external magnetic field  $B_0$  and that  $z_1$  due to the external static magnetic field  $B_1$  has the relationship  $z_1 < 0 < z_0$  (**FIG. 3B**).

[0009] When power microwave  $P_{IN}$  of frequency  $\Omega$  is input into the microwave cavity **32** of the CWC **30**, the microwave  $P_{IN}$  creates a transverse electric field alternating at the frequency  $\Omega$  in the interaction space **35** of the microwave cavity **32**. As the electron gun **31** generates a flow of electrons and the electron beam is sent into the center of the interaction space **35** by an electron lens, the electron beam rotates at the frequency  $\Omega$  (fast cyclotron rotation) due to the alternating transverse electric field in the space **35**.

[0010] In the transition space **34**, the rotating electron beam receives a Lorenz force in the radial direction due to

the reversed static magnetic field, so that the pitch angle of the velocity vector of the electron beam is deflected to the z direction, i.e., the z component of the velocity of the electron beam increases. This converts the movement of the electron beam into a helical movement, which means that the energy of the cyclotron wave is now converted into the energy of the synchronous wave of the same polarity.

[0011] The z-accelerated electron beam **36** enters the collector **33**, where the kinetic energy of the electron beam is extracted as a DC power in the load-resistance **37**.

[0012] CWC is potentially powerful and already tested at power level of 10 kW, which is rather well known from the previous different publications, in particularly from patents U.S. Pat. No. 3,462,636 and RU 2,119,691.

[0013] However, such type of CWC demands high intensity of static magnetic field that corresponds to the cyclotron frequency equal to the frequency of external microwave power source. This requirement usually creates essential technical problems, especially in the short centimetric and millimetric wavebands.

#### SUMMARY OF THE INVENTION

[0014] The present invention uses two microwave cavities having uniform and quadruple electric fields in the interaction spaces, which makes it possible to reduce the magnetic field intensity into half or less.

[0015] According to the present invention, a microwave/DC power converter includes:

- [0016] an electron source for generating a beam of electrons running on an axis;
  - [0017] a group of  $2n$  (where n is an even number) rod electrodes aligned symmetrically in parallel around the axis for receiving an externally supplied microwave and for giving the electron beam a rotational movement around the axis according to the microwave; and
  - [0018] a converter for converting the energy of the movement of the electron beam into a DC current.
- [0019] In a second form of the present invention, a microwave/DC power converter includes:
- [0020] an electron source for generating a beam of electrons running on an axis;
  - [0021] a first reactor for giving the electron beam an initial rotational movement;
  - [0022] a second reactor including a group of  $2n$  (where n is an even number) rod electrodes aligned symmetrically in parallel around the axis for receiving an externally supplied microwave and for giving the electron beam a cyclotron movement around the axis according to the microwave;
  - [0023] a kinetic converter for converting the cyclotron movement of the electron beam into an axial movement; and
  - [0024] a current converter for converting the electron beam in the axial movement into a DC current.
  - [0025] In the above microwave/DC power converter, the first reactor may preferably include a phase adjuster for

adjusting a phase of a rotational position of the electron beam with respect to the rod electrodes when the electron beam enters the second reactor. The microwave/DC power converter may further include a resistance which is provided between the electron source and both the first reactor and the second reactor in order to prevent an over current.

[0026] The microwave/DC power converter may further include an auxiliary electrode provided before the current converter, where a voltage applied on the auxiliary electrode is set slightly lower than a voltage applied on the current converter.

[0027] Since, in the microwave power converter of the present invention, the interaction of the electric field and the electron beam is operated at the frequency one n-th of that of conventional converters, the static magnetic field can be substantially reduced. This realized a compact, powerful and efficient microwave/DC power converter.

#### DRAWING DESCRIPTIONS

[0028] The invention will be better understood from a consideration of the ensuing description and attached Figures where similar references designate similar elements and in which:

[0029] FIG. 1A is a schema of an embodiment of the microwave/DC power converter according to the present invention;

[0030] FIG. 1B is a graph of the z component of the magnetic flux intensity on the z axis;

[0031] FIG. 2 is an equivalent diagram of the microwave/DC power converter of the above embodiment;

[0032] FIG. 3A is a schema of a conventional cyclotron wave converter; and

[0033] FIG. 3B is a graph of the z component of the magnetic flux intensity on the z axis of the conventional CWC.

#### DESCRIPTION OF PREFERRED EMBODIMENTS

[0034] FIG. 1A illustrates a schematic view of a CWC embodying the present invention, and FIG. 1B is a graph of  $B(z)$  or the z component of the magnetic flux intensity on the z axis which corresponds to that in FIG. 1A.  $F_c$  denotes the cyclotron frequency corresponding to  $B(z)$ . An electron gun 1 forms an electron beam 2 of a round cross section, which is injected along the z axis into a first microwave cavity 3 having a potential U equal to the potential U of the voltage source 12, because, at the normal operational mode, the current in resistor 13 is absent.

[0035] The first microwave cavity 3 has a resonant frequency equal to a half of the frequency F of the incoming power microwave P. A small part (<1%) of the power of the microwave P is split by the power splitter 6, and is fed via a frequency divider 5 and a phase shifter 4 to the first microwave cavity 3. Transverse electric field in the interaction space of the first microwave cavity 3 in combination with the resonant static and uniform magnetic field ( $F_c=F/2$ , see FIG. 1B) creates a small initial rotation of the electron beam around the z axis.

[0036] In the interaction space of a second microwave cavity 7 are placed four rod electrodes (quadrupole electrodes) in parallel with each other and symmetrically with respect to the z axis. The quadrupole electrodes are applied the small part of the microwave P having the frequency F. Since there are two pairs of electrodes in the quadrupole electrodes, the rotational frequency of the electron beam in the interaction space surrounded by the four rod electrodes is F/2. Thus the operation frequency of the first microwave cavity 3 is F/2. When 2n rod electrodes are placed similarly in the first microwave cavity 3, the rotational frequency of the electron beam is F/n, and the operation frequency of the first microwave cavity 3 is F/n.

[0037] In the same magnetic field, such an electric field ( $F_c=F/2$ ) in the quadrupole electrodes can accelerate or decelerate the transverse rotation of the electron beam depending on the initial (incoming) phase of the rotation. A phase shifter 4 makes it possible to set the initial phase at an optimal position at which the initial radius of the rotation will increase and energy of external microwave source will be effectively converted into the energy of electron beam rotation around the z axis.

[0038] A drift tube 8 has the same potential U (see FIG. 1A), but the static magnetic field is changed here in both the direction and the magnitude (region "REV" in FIG. 1B). The z component of the velocity of the rotating electron beam is increased in the divergent magnetic field of this region. The radial component of static magnetic field creates the process when the energy of the rotational movement of the electron beam is transferred into the additional energy of the z directional motion. Simultaneously, the electron beam configuration is changed: it takes the shape of a spatial helix (energy of fast cyclotron wave is transferred into the energy of synchronous wave of the same polarization). It is important to emphasize that optimal energy conversion in this region "REV" takes place always in asymmetrically reversed magnetic field (value of  $B_2$  is less than that  $B_1$  in FIG. 1B) for any real technical parameter of CWC.

[0039] After the region "REV", the accelerated electron beam enters the collector region 11, where its kinetic energy is extracted and transformed into DC energy which appears at the load resistance 14. The magnetic field distribution here depends on a concrete collector construction, and usually has a shape of decreasing field, as it is shown approximately in FIG. 1B by the dashed line. An additional electrode 9 is fed by voltage source 10, and has a potential a bit lower than the potential of the collector 11. This additional electrode 9 creates a local electric field just at the collector orifice, which protects against outcoming of the secondary emitted electrons.

[0040] Resistor 13 creates a simple current limiting system. Any small current (caused by microwave or DC overloads) to the walls of the first microwave cavity 3, the second microwave cavity 7 and the drift tube 8 will drop their potential essentially, and decrease of the electron gun current.

[0041] FIG. 2 shows an equivalent schema of the microwave cavities 3 and 7. The interaction space of the first microwave cavity 3 is shown along the z axis ( $y=0$  plane), and the quadrupole interaction space of the second microwave cavity 7 is given as a picture across the z axis ( $z=\text{const}$  plane). The first and the second microwave cavities 3 and 7

have different resonant frequencies, different electrode configuration, different equivalent capacities and inductivities. The first microwave cavity **3** creates a small initial rotation of the electron beam at the frequency equal to  $F/2$ . Such initial rotation is necessary for the interaction in the second microwave cavity **7** having electric field intensity equal to zero at the axis of the quadrupole field. **FIG. 2** shows the electrode potentials  $+V$ ,  $-V$  at some fixed moment of time. A cross section of the electron beam is shown as a bold black point “-e”, and corresponds to the optimal phase ( $y=-x$  for the center of this beam cross section). The adjustment of the position of the electron beam to the optimal phase can be made by the phase shifter **4**. The motion trajectory of the beam cross section is, as shown in **FIG. 2** by the dashed line, a circle.

[**0042**] Finally the invention covers all other variant embodiments open to any person skilled in the art and deriving from that described hereinbefore. As an example, a CWC having the second microwave cavity with six-pole electric field configuration (i.e.,  $n=3$ ) in combination with the first microwave cavity operating at the frequency equal to  $1/3$  of the frequency of the second one will have magnetic field reduced to a third and so on.

What is claimed is:

**1.** A microwave/DC power converter comprising:

- an electron source for generating a beam of electrons running on an axis;
- a group of  $2n$  (where  $n$  is an even number) rod electrodes aligned symmetrically in parallel around the axis for receiving an externally supplied microwave and for giving the electron beam a rotational movement around the axis according to the microwave; and
- a converter for converting the energy of the movement of the electron beam into a DC current.

**2.** A microwave/DC cyclotron wave converter comprising:

- an electron source for generating a beam of electrons running on an axis;
- a first reactor for giving the electron beam an initial rotational movement;
- a second reactor including a group of  $2n$  (where  $n$  is an even number) rod electrodes aligned symmetrically in parallel around the axis for receiving an externally supplied microwave and for giving the electron beam a cyclotron movement around the axis according to the microwave;
- a kinetic converter for converting the cyclotron movement of the electron beam into an axial movement; and
- a current converter for converting the electron beam in the axial movement into a DC current.

**3.** The microwave/DC power converter according to claim 2, wherein the first reactor includes a phase adjuster for adjusting a phase of a rotational position of the electron beam with respect to the rod electrodes when the electron beam enters the second reactor.

**4.** The microwave/DC power converter according to claim 3, wherein the microwave/DC power converter further comprises a resistance provided between the electron source and both the first reactor and the second reactor for preventing an over current.

**5.** The microwave/DC power converter according to claim 3, wherein the microwave/DC power converter further comprises an auxiliary electrode provided before the current converter, where a voltage applied on the auxiliary electrode is slightly lower than a voltage applied on the current converter.

\* \* \* \* \*