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(54) Title: METHOD FOR AUTOMATIC ADJUSTMENT OF AN ION CYCLOTRON RESONANCE HEATING SYSTEM OF A THERMONUCLEAR REACTOR

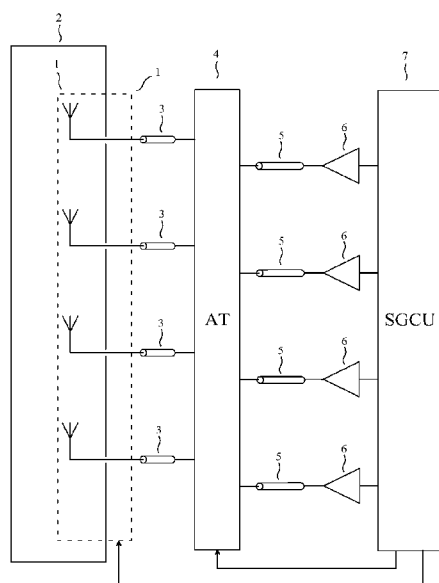


FIG. 1

(57) Abstract: A thermonuclear reactor of the invention comprises an ion cyclotron resonance heating system, the ion cyclotron resonance heating system comprising: a tunable antenna (1) having 4 signal ports, the tunable antenna allowing a transfer of power from its signal ports to an electromagnetic field produced in a vacuum chamber (2); a multiple-input-port and multiple-output-port tuning unit (4) having 4 input ports and 4 output ports, each of the output ports being indirectly coupled to one and only one of the signal ports through a coaxial transmission line (3); 4 high-power radio-frequency amplifiers (6), the output of each of which being indirectly coupled to one and only one of the 4 input ports through a coaxial transmission line (5); and a signal generation and control unit (7).

Method for automatic adjustment of an ion cyclotron resonance heating system of a thermonuclear reactor

FIELD OF THE INVENTION

5 The invention relates to a method for automatically adjusting an ion cyclotron resonance heating system of a thermonuclear reactor. The invention also relates to a thermonuclear reactor implementing this method.

The French patent application No. FR2108661 of 12 August 2021, entitled “Procédé pour réglage automatique d’un système de chauffage à résonance cyclotronique ionique d’un réacteur
10 thermonucléaire” is incorporated by reference.

PRIOR ART

In what follows, X and Y being different quantities or variables, performing an action as a function of X does not preclude the possibility of performing this action as a function of Y. In what follows, “coupled” always refers to an electric coupling. When applied to two items such
15 as terminals, conductors, nodes, etc, “coupled” may indicate that the items are directly coupled, that is to say connected to (or, equivalently, in electric contact with) one another, or that the items are indirectly coupled, in which case an electric interaction different from direct coupling exists between the items, for instance through one or more components. When applied to two
20 multi-terminal items, such as ports, connectors, etc, “coupled” may indicate that the items are directly coupled, in which case each terminal of one of the items is directly coupled to one and only one terminal of the other item, or that the items are indirectly coupled, in which case an electric interaction different from direct coupling exists between the terminals of the items, for instance through one or more components.

Ion cyclotron resonance heating, also called “ICRH” or “ion cyclotron radio-frequency
25 heating”, is referred to as “chauffage à résonance cyclotronique ionique” or “chauffage cyclotronique ionique” in French. Ion cyclotron resonance heating is one of the standard plasma heating techniques used in thermonuclear reactors based on a magnetic confinement of the hot plasma (these thermonuclear reactors are usually referred to as “tokamaks”). An ion cyclotron resonance heating system may for instance operate in the 35 MHz to 65 MHz frequency range.
30 To obtain an heating power larger than 5 MW in this frequency range, it is advisable to use a plurality of radio-frequency amplifiers, a multiport antenna, and a multiple-input-port and multiple-output-port tuning unit. The multiple-input-port and multiple-output-port tuning unit is used to obtain that each radio-frequency amplifier sees an optimal or almost optimal load, for any behaviour of the plasma, except, possibly, if an edge localized mode (also referred to as
35 ELM) occurs in the vacuum chamber of the thermonuclear reactor.

Thus, in a thermonuclear reactor comprising an ion cyclotron resonance heating system, the ion cyclotron resonance heating system may comprise:

an antenna, the antenna having n ports each referred to as “signal port”, where n is an integer greater than or equal to 2, the antenna allowing, at a given frequency, a transfer of power from the n signal ports to an electromagnetic field produced by the antenna in a vacuum chamber of the thermonuclear reactor;

a multiple-input-port and multiple-output-port tuning unit having m input ports and n output ports, where m is an integer greater than or equal to 2, the multiple-input-port and multiple-output-port tuning unit comprising p adjustable impedance devices, where p is an integer greater than or equal to m , the p adjustable impedance devices being referred to as the “adjustable impedance devices of the tuning unit” and being such that, at the given frequency, each of the adjustable impedance devices of the tuning unit has a reactance, the reactance of any one of the adjustable impedance devices of the tuning unit being adjustable by electrical means, each of the n output ports being directly or indirectly coupled to one and only one of the signal ports; and

m high-power radio-frequency amplifiers, each of the high-power radio-frequency amplifiers having an output, the output of said each of the high-power radio-frequency amplifiers being directly or indirectly coupled to one and only one of the m input ports, the output of said each of the high-power radio-frequency amplifiers being used to apply an excitation to the input port to which it is directly or indirectly coupled.

The thermonuclear reactor further comprises a plurality of sensing units installed at different places in the ion cyclotron resonance heating system, each of the sensing units comprising a directional coupler used to sense two electrical variables in the ion cyclotron resonance heating system, to obtain “sensing unit output signals”, each of the sensing unit output signals being mainly determined by one of the electrical variables sensed in the ion cyclotron resonance heating system.

According to the prior art, such a thermonuclear reactor is characterized in that, a “selected frequency” being chosen, one applies m excitations to the m input ports, one and only one of the excitations being applied to each of the input ports, each of the excitations being an unmodulated carrier having a frequency which is equal to the selected frequency.

According to the prior art, the sensing unit output signals are used to automatically adjust the ion cyclotron resonance heating system, by utilizing an extremum-seeking control algorithm which adjusts, by electrical means, the reactance of one or more of the adjustable impedance devices of the tuning unit, to get closer to an extremum of a performance variable, the performance variable being a real function of the sensing unit output signals. This type of control system is slow. Thus, the prior art does not teach a fast and accurate method for automatically adjusting the ion cyclotron resonance heating system of the thermonuclear reactor. Consequently, according to the prior art, to avoid a degradation of the high-power radio-

frequency amplifiers, in particular when an edge localized mode occurs, radio-frequency power must be wasted in loads (sometimes referred to as “dummy loads”) whenever the adjustment is not correct, and/or the high-power radio-frequency amplifiers must permanently operate at a reduced output power, compared to their theoretical maximum output power.

5 The specialist consequently understands that the prior art does not teach a method for automatically adjusting an ion cyclotron resonance heating system of a thermonuclear reactor, which maximizes the power that the ion cyclotron resonance heating system can deliver to the plasma existing in the vacuum chamber of the thermonuclear reactor.

SUMMARY OF THE INVENTION

10 The purpose of the invention is a method for automatically adjusting an ion cyclotron resonance heating system of a thermonuclear reactor, which maximizes the power that the ion cyclotron resonance heating system can deliver to the plasma existing in the vacuum chamber of the thermonuclear reactor.

The method of the invention is a method for automatically adjusting an ion cyclotron
15 resonance heating system of a thermonuclear reactor, the ion cyclotron resonance heating system comprising a tunable antenna and a multiple-input-port and multiple-output-port tuning unit, the tunable antenna having n ports each referred to as “signal port”, where n is an integer greater than or equal to 2, the tunable antenna allowing, at a given frequency, a transfer of power from the n signal ports to an electromagnetic field produced by the tunable antenna in a vacuum
20 chamber of the thermonuclear reactor, the tunable antenna comprising at least one antenna control device having at least one antenna control device parameter, said at least one antenna control device parameter having an effect on one or more characteristics of the tunable antenna, said at least one antenna control device parameter being adjustable by electrical means, the multiple-input-port and multiple-output-port tuning unit having m input ports and n output ports,
25 where m is an integer greater than or equal to 2, the multiple-input-port and multiple-output-port tuning unit comprising p adjustable impedance devices, where p is an integer greater than or equal to m , the p adjustable impedance devices being referred to as the “adjustable impedance devices of the tuning unit” and being such that, at the given frequency, each of the adjustable impedance devices of the tuning unit has a reactance, the reactance of any one of the adjustable
30 impedance devices of the tuning unit being adjustable by electrical means, each of the n output ports being directly or indirectly coupled to one and only one of the signal ports, the method comprising the steps of:

selecting a frequency referred to as the “selected frequency”;

adjusting, by electrical means, at least one of the one or more antenna control device
35 parameters;

applying m excitations to the m input ports, one and only one of the excitations being applied to each of the input ports, each of the excitations being a bandpass signal having a carrier frequency and a complex envelope, the carrier frequency of said each of the excitations being equal to the selected frequency, the m complex envelopes of the m excitations being linearly independent in the set of complex functions of one real variable, regarded as a vector space over the field of complex numbers;

sensing, at each of m or more places in the ion cyclotron resonance heating system, one or more electrical variables, to obtain “sensing unit output signals”, each of the sensing unit output signals being mainly determined by at least one of the electrical variables sensed at one of said m or more places in the ion cyclotron resonance heating system;

estimating q tuning parameters by utilizing the sensing unit output signals, where q is an integer greater than or equal to m , each of the tuning parameters being a quantity depending on an impedance matrix seen by the output ports; and

adjusting, by electrical means, the reactance of one or more of the adjustable impedance devices of the tuning unit, as a function of the q tuning parameters.

Said multiple-input-port and multiple-output-port tuning unit comprises m input ports and n output ports. It is assumed that said multiple-input-port and multiple-output-port tuning unit behaves, at said given frequency, with respect to its input ports and output ports, substantially as a passive linear device, where “passive” is used in the meaning of circuit theory. More precisely, said multiple-input-port and multiple-output-port tuning unit normally behaves, at said given frequency, with respect to the n output ports and the m input ports, substantially as a passive linear $(n + m)$ -port device.

For instance, one or more of the q tuning parameters may be substantially proportional to the absolute value, or the phase, or the real part, or the imaginary part of an entry of said impedance matrix seen by the output ports, or of an entry of the inverse of said impedance matrix seen by the output ports (this inverse being an admittance matrix seen by the output ports), or of an entry of a scattering matrix seen by the output ports.

An impedance matrix presented by the input ports depends on said impedance matrix seen by the output ports. Consequently, one or more of the q tuning parameters may for instance be substantially proportional to the absolute value, or the phase, or the real part, or the imaginary part of an entry of said impedance matrix presented by the input ports, or of an entry of the inverse of said impedance matrix presented by the input ports (this inverse being an admittance matrix presented by the input ports), or of an entry of a scattering matrix presented by the input ports.

For instance, it is possible that said m complex envelopes are such that the influence of any one of the excitations on each of at least m of the electrical variables can be determined from the knowledge of said m complex envelopes and of the sensing unit output signals. In the previous sentence, “the electrical variables” means “the m or more electrical variables sensed at said m

or more places in the ion cyclotron resonance heating system”, and “can be determined” means “can be determined with a sufficient accuracy, for instance a relative accuracy less than 5 per cent, or less than 1 per cent”.

For instance, it is possible that the method of the invention further comprises the step of using one or more of the sensing unit output signals, to activate one or more warning signals if the presence of an edge localized mode is suspected or detected in the vacuum chamber of the thermonuclear reactor. In this case, it is possible that the method of the invention further comprises the step of reducing a power of the excitations, for a given time, if one of the one or more warning signals has been activated; and it is possible that the reactance of one or more of the adjustable impedance devices of the tuning unit is adjusted as a function of the q tuning parameters and as a function of the possible activation of one or more of the one or more warning signals.

For instance, it is possible that an average power of the excitations does not vary over time, if there is no activation of one of the one or more warning signals.

For instance, it is possible that each of the excitations is an amplitude modulated carrier, the modulation factor being for instance less than or equal to 4 percent for each of the excitations. Such a modulation can be used to obtain that said m complex envelopes are linearly independent in the set of complex functions of one real variable, and that an average power of the excitations does not vary over time, if there is no activation of one of the one or more warning signals.

For instance, it is possible that each of the excitations is a phase modulated carrier, the phase variation produced by the modulation being for instance less than or equal to 5 degree for each of the excitations. Such a modulation can be used to obtain that said m complex envelopes are linearly independent in the set of complex functions of one real variable, and that an average power of the excitations does not vary over time, if there is no activation of one of the one or more warning signals.

For instance, it is possible that a numerical model is utilized in the step of adjusting, by electrical means, the reactance of one or more of the adjustable impedance devices of the tuning unit, as a function of the q tuning parameters.

An apparatus implementing the method of the invention is a thermonuclear reactor comprising an ion cyclotron resonance heating system, the ion cyclotron resonance heating system comprising:

a tunable antenna, the tunable antenna having n ports each referred to as “signal port”, where n is an integer greater than or equal to 2, the tunable antenna allowing, at a given frequency, a transfer of power from the n signal ports to an electromagnetic field produced by the tunable antenna in a vacuum chamber of the thermonuclear reactor, the tunable antenna comprising at least one antenna control device having at least one antenna control device parameter, said at least one antenna control device parameter having an effect on one or more characteristics of the tunable antenna, said at least one antenna control device parameter being adjustable by electrical means; and

a multiple-input-port and multiple-output-port tuning unit having m input ports and n output ports, where m is an integer greater than or equal to 2, the multiple-input-port and multiple-output-port tuning unit comprising p adjustable impedance devices, where p is an integer greater than or equal to m , the p adjustable impedance devices being referred to as the “adjustable impedance devices of the tuning unit” and being such that, at the given frequency, each of the adjustable impedance devices of the tuning unit has a reactance, the reactance of any one of the adjustable impedance devices of the tuning unit being adjustable by electrical means, each of the n output ports being directly or indirectly coupled to one and only one of the signal ports;

5

10 the thermonuclear reactor being characterized in that it further comprises means for:

- selecting a frequency referred to as the “selected frequency”;
- adjusting, by electrical means, at least one of the one or more antenna control device parameters;
- applying m excitations to the m input ports, one and only one of the excitations being applied to each of the input ports, each of the excitations being a bandpass signal having a carrier frequency and a complex envelope, the carrier frequency of said each of the excitations being equal to the selected frequency, the m complex envelopes of the m excitations being linearly independent in the set of complex functions of one real variable, regarded as a vector space over the field of complex numbers;
- 15
- 20 sensing, at each of m or more places in the ion cyclotron resonance heating system, one or more electrical variables, to obtain “sensing unit output signals”, each of the sensing unit output signals being mainly determined by at least one of the electrical variables sensed at one of said m or more places in the ion cyclotron resonance heating system;
- estimating q tuning parameters by utilizing the sensing unit output signals, where q is an integer greater than or equal to m , each of the tuning parameters being a quantity depending on an impedance matrix seen by the output ports; and
- 25
- adjusting, by electrical means, the reactance of one or more of the adjustable impedance devices of the tuning unit, as a function of the q tuning parameters.

For instance, it is possible that a numerical model is utilized for adjusting, by electrical means, the reactance of one or more of the adjustable impedance devices of the tuning unit, as a function of the q tuning parameters.

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BRIEF DESCRIPTION OF THE DRAWINGS

Other advantages and characteristics will appear more clearly from the following description of particular embodiments of the invention, given by way of non-limiting examples, with reference to the accompanying drawings in which:

- Figure 1 shows a block diagram of an ion cyclotron resonance heating system of a thermonuclear reactor of the invention (first and second embodiments); and
- Figure 2 shows a block diagram of an ion cyclotron resonance heating system of a thermonuclear reactor of the invention (third embodiment).

5 DETAILED DESCRIPTION OF SOME EMBODIMENTS

First embodiment.

As a first embodiment of a device of the invention, given by way of non-limiting example, we have represented in Figure 1 the block diagram of an ion cyclotron resonance heating system of a thermonuclear reactor of the invention, the ion cyclotron resonance heating system being
10 intended to be able to deliver an average power of at least 10 MW, the ion cyclotron resonance heating system comprising:

a tunable antenna (1), the tunable antenna having $n = 4$ ports each referred to as “signal port”, the tunable antenna allowing, at a given frequency chosen in the 50 MHz to 90 MHz frequency range, a transfer of power from the n signal ports to an
15 electromagnetic field produced by the tunable antenna in a vacuum chamber (2) of the thermonuclear reactor, the tunable antenna comprising at least one antenna control device having at least one antenna control device parameter, said at least one antenna control device parameter having an effect on one or more characteristics of the tunable antenna, said at least one antenna control device parameter being adjustable by
20 electrical means, the tunable antenna comprising a window acting as a vacuum and tritium barrier;

a multiple-input-port and multiple-output-port tuning unit (4), also referred to as “multiple-antenna-port antenna tuner”, having $m = 4$ input ports and n output ports, the multiple-input-port and multiple-output-port tuning unit comprising p adjustable
25 impedance devices, where p is an integer greater than or equal to m , the p adjustable impedance devices being referred to as the “adjustable impedance devices of the tuning unit” and being such that, at the given frequency, each of the adjustable impedance devices of the tuning unit has a reactance, the reactance of any one of the adjustable impedance devices of the tuning unit being adjustable by electrical means,
30 each of the n output ports being indirectly coupled to one and only one of the signal ports through a coaxial transmission line (3);

m high-power radio-frequency amplifiers (6) which can each deliver 3 MW at the given frequency, each of the high-power radio-frequency amplifiers having an output, the output of said each of the high-power radio-frequency amplifiers being indirectly
35 coupled to one and only one of the m input ports through a coaxial transmission line (5); and

a signal generation and control unit (7);

the thermonuclear reactor being characterized in that:

the signal generation and control unit selects a frequency referred to as the “selected frequency”, in the 50 MHz to 90 MHz frequency range;

5 the signal generation and control unit adjusts, by electrical means, at least one of the one or more antenna control device parameters;

the signal generation and control unit delivers, to the high-power radio-frequency amplifiers, signals such that the high-power radio-frequency amplifiers are used to apply m excitations to the m input ports, one and only one of the excitations being applied to each of the input ports, each of the excitations being a bandpass signal having a carrier frequency and a complex envelope, the carrier frequency of said each of the excitations being equal to the selected frequency, the m complex envelopes of the m excitations being linearly independent in the set of complex functions of one real variable, regarded as a vector space over the field of complex numbers;

15 m sensing units, which are not shown in Figure 1, are used to sense, at each of the m input ports, one or more electrical variables, to obtain “sensing unit output signals”, each of the sensing unit output signals being mainly determined by at least one of the electrical variables sensed at one of the m input ports;

the signal generation and control unit estimates q tuning parameters by utilizing the sensing unit output signals, where $q = 2m^2$, each of the tuning parameters being a real quantity depending on an impedance matrix seen by the output ports; and

the signal generation and control unit adjusts, by electrical means, the reactances of the adjustable impedance devices of the tuning unit, as a function of the q tuning parameters.

25 An average power of the excitations does not vary over time.

Each of the excitations is a bandpass signal (in French: “signal passe-bande”). This type of signal is sometimes improperly referred to as “passband signal” or “narrow-band signal” (in French: “signal à bande étroite”). A bandpass signal is any real signal $s(t)$, where t denotes the time, such that the spectrum of $s(t)$ is included in a frequency interval $[f_c - W/2, f_c + W/2]$, where f_c is a frequency referred to as “carrier frequency” and W is a frequency referred to as “bandwidth”, which satisfies $W < 2f_c$. Thus, the Fourier transform of $s(t)$, denoted by $S(f)$, is non-negligible only in the frequency intervals $[-f_c - W/2, -f_c + W/2]$ and $[f_c - W/2, f_c + W/2]$. The complex envelope of the real signal $s(t)$, also referred to as “complex baseband equivalent” or “baseband-equivalent signal”, is a complex signal $s_B(t)$ whose Fourier transform $S_B(f)$ is non-negligible only in the frequency interval $[-W/2, W/2]$ and satisfies $S_B(f) = k S(f_c + f)$ in this interval, where k is a real constant which is chosen equal to the square root of 2 by some authors. The real part of $s_B(t)$ is referred to as the in-phase component, and the imaginary part of $s_B(t)$ is referred to as the quadrature component. The specialist knows that the bandpass signal $s(t)$ may for instance be obtained:

- as the result of a phase and amplitude modulation of a single carrier at the frequency f_C ;
- as a linear combination of a first signal and a second signal, the first signal being the product of the in-phase component and a first sinusoidal carrier of frequency f_C , the second signal being the product of the quadrature component and a second sinusoidal carrier of frequency f_C , the second sinusoidal carrier being 90° out of phase with respect to the first sinusoidal carrier;
- 5 - in other ways, for instance without using any carrier, for instance using directly a filtered output of a digital-to-analog converter.

The frequency interval $[f_C - W/2, f_C + W/2]$ is a passband of the bandpass signal. From the definitions, it is clear that, for a given bandpass signal, several choices of carrier frequency f_C and of bandwidth W are possible, so that the passband of the bandpass signal is not uniquely defined. However, any passband of the bandpass signal must contain any frequency at which the spectrum of $s(t)$ is not negligible.

The complex envelope of the real signal $s(t)$ clearly depends on the choice of a carrier frequency f_C . However, for a given carrier frequency, the complex envelope of the real signal $s(t)$ is uniquely defined, for a given choice of the real constant k .

One and only one of said m excitations is applied to each of the input ports, the m excitations being applied simultaneously. Each of said m excitations is a bandpass signal having a passband which contains the selected frequency. The selected frequency being considered as the carrier frequency, each of the excitations has one and only one complex envelope, the m complex envelopes of the m excitations being linearly independent in E , where E is the set of complex functions of one real variable, regarded as a vector space over the field of complex numbers.

The q tuning parameters are sufficient to allow a determination of an impedance matrix presented by the input ports (which depends on the impedance matrix seen by the output ports).

25 The wording “are sufficient to allow a determination of an impedance matrix presented by the input ports” does not imply that an impedance matrix presented by the input ports is determined, but it is possible that an impedance matrix presented by the input ports is determined.

The information carried by the sensing unit output signals must be sufficient to allow the signal generation and control unit to estimate the q tuning parameters. The sensing units may for instance be such that, for any one of the input ports, the sensing unit output signals comprise: a first sensing unit output signal proportional to a first electrical variable, the first electrical variable being a voltage across said any one of the input ports; and a second sensing unit output signal proportional to a second electrical variable, the second electrical variable being a current flowing in said any one of the input ports. Said voltage across said any one of the input ports may be a complex voltage and said current flowing in said any one of the input ports may be a complex current. Alternatively, the sensing units may for instance be such that, for any one of the input ports, the sensing unit output signals comprise: a first sensing unit output signal proportional to a first electrical variable, the first electrical variable being an incident voltage

(which may also be referred to as “forward voltage”) at said any one of the input ports; and a second sensing unit output signal proportional to a second electrical variable, the second electrical variable being a reflected voltage at said any one of the input ports. Said incident voltage at said any one of the input ports may be a complex incident voltage and said reflected voltage at said any one of the input ports may be a complex reflected voltage.

The specialist understands how such sensing unit output signals can be processed to for instance obtain that the $2m^2$ tuning parameters describe an impedance matrix presented by the input ports (for instance, m^2 tuning parameters being each a real number proportional to the real part of an entry of this impedance matrix, and m^2 tuning parameters being each a real number proportional to the imaginary part of an entry of this impedance matrix), or to for instance obtain that the $2m^2$ tuning parameters describe a scattering matrix presented by the input ports (for instance, m^2 tuning parameters being each a real number proportional to the absolute value of an entry of this scattering matrix, and m^2 tuning parameters being each a real number proportional to a phase of an entry of this scattering matrix). For instance, suitable explanations are provided in Appendix C of the article of F. Broydé and E. Clavelier entitled “A Typology of Antenna Tuner Control Schemes, for One or More Antennas”, published in *Excem Research Papers in Electronics and Electromagnetics*, no. 1 (doi: 10.5281/zenodo.3902749) in June 2020.

In what follows, in line with the “IEC multilingual dictionary of electricity” edited by the *Bureau Central de la Commission Electrotechnique Internationale* in 1983, “open-loop control” means control which does not utilize a measurement of the controlled variable, and “closed-loop control” (which is also referred to as “feedback control”) means control in which the control action is made to depend on a measurement of the controlled variable.

The nominal reactance of each of the adjustable impedance devices of the tuning unit is, at a given point in time, determined by the signal generation and control unit as a function of a “tuning unit adjustment instruction”, which is generated inside the signal generation and control unit. A new tuning unit adjustment instruction is generated repeatedly. For instance, a new tuning unit adjustment instruction may be generated periodically, for instance every 20 microseconds. Each of the tuning unit adjustment instructions may be of any type of digital message. Each of the tuning unit adjustment instructions is used by the signal generation and control unit to determine “tuning control signals”, which are delivered to the multiple-input-port and multiple-output-port tuning unit to control the reactances of the adjustable impedance devices of the tuning unit.

The ion cyclotron resonance heating system uses a closed-loop control scheme based on a model, in which at least one of the tuning unit adjustment instructions is determined as a function of:

- one or more quantities determined by the selected frequency;
- one or more variables determined by one or more of the previous tuning unit adjustment instructions; and
- the q tuning parameters.

The model is a numerical model which describes the effect of the tuning control signals on the reactances of the adjustable impedance devices of the tuning unit. The numerical model may also be such that it takes into account the effect of one or more temperatures measured in the ion cyclotron resonance heating system, on the reactances of the adjustable impedance devices of the tuning unit.

Some model-based closed-loop control schemes, suitable for controlling a multiple-antenna-port antenna tuner of a radio transmitter, are disclosed in international application number PCT/IB2019/051501 of 25 February 2019 (WO 2019/180520), entitled “Method of automatic adjustment of a tuning unit, and apparatus for radio communication using this method”, and are discussed in Section XI of said article entitled “A Typology of Antenna Tuner Control Schemes, for One or More Antennas”, where they are referred to as “type 1 subtype *c*”. The specialist understands how he can adapt the teaching of this international application and this article, to the present ion cyclotron resonance heating system of a thermonuclear reactor of the invention. In particular, the specialist understands that the thermonuclear reactor of the invention implements a very fast and very accurate method for automatically adjusting an ion cyclotron resonance heating system of a thermonuclear reactor.

Thus, there is no need to waste radio-frequency power in loads whenever the adjustment is not correct, and/or to operate the high-power radio-frequency amplifiers at a reduced output power, compared to their theoretical maximum output power. Since the multiple-input-port and multiple-output-port tuning unit is such that it can provide, at said selected frequency, for suitable values of the tuning control signals, a low-loss transfer of power from the input ports to the output ports, it follows that the invention maximizes the power that the ion cyclotron resonance heating system can deliver to the plasma existing in the vacuum chamber of the thermonuclear reactor.

25 Second embodiment.

As a second embodiment of a device of the invention, given by way of non-limiting example, we have represented in Figure 1 the block diagram of an ion cyclotron resonance heating system of a thermonuclear reactor of the invention, the ion cyclotron resonance heating system comprising:

30 a tunable antenna (1), the tunable antenna having $n = 4$ ports each referred to as “signal port”, the tunable antenna allowing, at a given frequency, a transfer of power from the n signal ports to an electromagnetic field produced by the tunable antenna in a vacuum chamber (2) of the thermonuclear reactor, the tunable antenna comprising at least one antenna control device having at least one antenna control device parameter, said at least one antenna control device parameter having an effect on one or more characteristics of the tunable antenna, said at least one antenna control device parameter being adjustable by electrical means;

a multiple-input-port and multiple-output-port tuning unit (4), also referred to as “multiple-antenna-port antenna tuner”, having $m = 4$ input ports and n output ports, the multiple-input-port and multiple-output-port tuning unit comprising p adjustable impedance devices, where p is an integer equal to $m(m + 1)$, the p adjustable impedance devices being referred to as the “adjustable impedance devices of the tuning unit” and being such that, at the given frequency, each of the adjustable impedance devices of the tuning unit has a reactance, the reactance of any one of the adjustable impedance devices of the tuning unit being adjustable by electrical means, each of the n output ports being indirectly coupled to one and only one of the signal ports through a transmission line (3); and

m radio-frequency amplifiers (6), each of the radio-frequency amplifiers having an output, the output of said each of the radio-frequency amplifiers being indirectly coupled to one and only one of the m input ports through a transmission line (5);

the thermonuclear reactor further comprising a signal generation and control unit (7), and being characterized in that:

- the signal generation and control unit selects a frequency referred to as the “selected frequency”;
- the signal generation and control unit adjusts, by electrical means, at least one of the one or more antenna control device parameters, as a function of the selected frequency;
- the signal generation and control unit delivers, to the radio-frequency amplifiers, signals such that the radio-frequency amplifiers are used to apply m excitations to the m input ports, one and only one of the excitations being applied to each of the input ports, each of the excitations being a bandpass signal having a carrier frequency and a complex envelope, the carrier frequency of said each of the excitations being equal to the selected frequency, the m complex envelopes of the m excitations being linearly independent in the set of complex functions of one real variable, regarded as a vector space over the field of complex numbers;
- n sensing units, which are not shown in Figure 1, are used to sense, at each of the n output ports, one or more electrical variables, to obtain “sensing unit output signals”, each of the sensing unit output signals being mainly determined by at least one of the electrical variables sensed at one of the n output ports;
- the signal generation and control unit uses one or more of the sensing unit output signals, to activate one or more warning signals if the presence of an edge localized mode is suspected in the vacuum chamber of the thermonuclear reactor;
- the signal generation and control unit reduces a power of the excitations by substantially 20 per cent, for a given time equal to one millisecond, if one of the one or more warning signals has been activated;

the signal generation and control unit estimates q tuning parameters by utilizing the sensing unit output signals, where $q = 2n^2$, each of the tuning parameters being a real quantity depending on an impedance matrix seen by the output ports; and

5 the signal generation and control unit adjusts, by electrical means, the reactances of the adjustable impedance devices of the tuning unit, as a function of the q tuning parameters and as a function of the possible activation of one or more of the one or more warning signals.

Many different types of antenna control device may be used to control one or more characteristics of a tunable antenna. An antenna control device may for instance be:

- 10 - an electrically controlled switch or change-over switch, in which case a parameter of the antenna control device having an effect on one or more characteristics of the tunable antenna may be the state of the switch or change-over switch;
- an adjustable impedance device, in which case a parameter of the antenna control device having an effect on one or more characteristics of the tunable antenna may be the reactance
15 or the impedance of the adjustable impedance device at a specified frequency; or
- an actuator arranged to produce a mechanical deformation of the tunable antenna, in which case a parameter of the antenna control device having an effect on one or more characteristics of the tunable antenna may be a length of the deformation.

The article of F. Broydé and E. Clavelier entitled “Some Properties of Multiple-Antenna-
20 Port and Multiple-User-Port Antenna Tuners”, published in *IEEE Trans. on Circuits and Systems — I: Regular Papers*, Vol. 62, No. 2, pp. 423-432, in February 2015, and Section XI of said article entitled “A Typology of Antenna Tuner Control Schemes, for One or More Antennas” explain the advantage of having p greater than or equal to $m(m + 1)$.

The q tuning parameters are sufficient to allow a determination of the impedance matrix
25 seen by the output ports. The wording “are sufficient to allow a determination of the impedance matrix seen by the output ports” does not imply that the impedance matrix seen by the output ports is determined, but it is possible that the impedance matrix seen by the output ports is determined.

The information carried by the sensing unit output signals must be sufficient to allow the
30 signal generation and control unit to estimate the q tuning parameters. The sensing units may for instance be such that, for any one of the output ports, the sensing unit output signals comprise: a first sensing unit output signal proportional to a first electrical variable, the first electrical variable being a voltage across said any one of the output ports; and a second sensing unit output signal proportional to a second electrical variable, the second electrical variable
35 being a current flowing out of said any one of the output ports. Said voltage across said any one of the output ports may be a complex voltage and said current flowing out of said any one of the output ports may be a complex current. Alternatively, the sensing units may for instance be such that, for any one of the output ports, the sensing unit output signals comprise: a first sensing unit

output signal proportional to a first electrical variable, the first electrical variable being an incident voltage (which may also be referred to as “forward voltage”) at said any one of the output ports; and a second sensing unit output signal proportional to a second electrical variable, the second electrical variable being a reflected voltage at said any one of the output ports. Said incident voltage at said any one of the output ports may be a complex incident voltage and said reflected voltage at said any one of the output ports may be a complex reflected voltage.

The specialist understands how such sensing unit output signals can be processed to for instance obtain that the $2n^2$ tuning parameters describe an impedance matrix seen by the output ports, or to for instance obtain that the $2n^2$ tuning parameters describe a scattering matrix seen by the output ports. For instance, suitable explanations are provided in Appendix C of said article entitled “A Typology of Antenna Tuner Control Schemes, for One or More Antennas”.

The nominal reactance of each of the adjustable impedance devices of the tuning unit is, at a given point in time, determined by the signal generation and control unit as a function of a “tuning unit adjustment instruction”, which is generated inside the signal generation and control unit. A new tuning unit adjustment instruction is generated repeatedly.

The specialist knows how the sensing unit output signals can be used to detect the presence of an edge localized mode in the vacuum chamber of the thermonuclear reactor, for instance based on the presence of fast and large variations of reflection coefficients.

The ion cyclotron resonance heating system uses an open-loop control scheme, this control scheme being consequently based on a model. The open-loop control scheme is such that: if one of the one or more warning signals is activated, then no new tuning unit adjustment instruction is generated; and if none of the one or more warning signals is activated, then a new tuning unit adjustment instruction is generated periodically, as a function of one or more quantities depending on the selected frequency, and as a function of the q tuning parameters.

The model is a numerical model which describes the effect of a tuning unit adjustment instruction on the reactances of the adjustable impedance devices of the tuning unit, and/or on the characteristics of the multiple-input-port and multiple-output-port tuning unit. The numerical model may also be such that it takes into account the effect of one or more temperatures measured in the ion cyclotron resonance heating system, on the reactances of the adjustable impedance devices of the tuning unit, and/or on the characteristics of the multiple-input-port and multiple-output-port tuning unit.

Some model-based open-loop control schemes, suitable for controlling a multiple-antenna-port antenna tuner of a radio transmitter, are disclosed in international application number PCT/IB2015/057161 of 17 September 2015 (WO 2017/033048), entitled “Method for automatically adjusting a tuning unit, and automatic tuning system using this method”, and are discussed in Section XI of said article entitled “A Typology of Antenna Tuner Control Schemes, for One or More Antennas”, where they are referred to as “type 3”. The specialist understands how he can adapt the teaching of this international application and this article, to

the present ion cyclotron resonance heating system of a thermonuclear reactor of the invention. In particular, the specialist understands that the thermonuclear reactor of the invention implements an accurate and very fast method for automatically adjusting an ion cyclotron resonance heating system of a thermonuclear reactor.

5 Thus, there is no need to waste radio-frequency power in loads whenever the adjustment is not correct, and/or to permanently operate the radio-frequency amplifiers at a reduced output power, compared to their theoretical maximum output power. Since the multiple-input-port and multiple-output-port tuning unit is such that it can provide, at said selected frequency, for suitable adjustments of the reactances of the adjustable impedance devices of the tuning unit,
10 a low-loss transfer of power from the input ports to the output ports, it follows that the invention maximizes the power that the ion cyclotron resonance heating system can deliver to the plasma existing in the vacuum chamber of the thermonuclear reactor.

Third embodiment (best mode).

As a third embodiment of a device of the invention, given by way of non-limiting example
15 and best mode of carrying out the invention, we have represented in Figure 2 the block diagram of an ion cyclotron resonance heating system of a thermonuclear reactor of the invention, the ion cyclotron resonance heating system being intended to be able to deliver an average power of at least 10 MW, the ion cyclotron resonance heating system comprising:

a tunable antenna (1), the tunable antenna having $n = 8$ ports each referred to as “signal
20 port”, the tunable antenna allowing, at a given frequency chosen in the 35 MHz to 65 MHz frequency range, a transfer of power from the n signal ports to an electromagnetic field produced by the tunable antenna in a vacuum chamber (2) of the thermonuclear reactor, the tunable antenna comprising at least one antenna control device having at least one antenna control device parameter, said at least one antenna
25 control device parameter having an effect on one or more characteristics of the tunable antenna, said at least one antenna control device parameter being adjustable by electrical means;

a multiple-input-port and multiple-output-port tuning unit (4), also referred to as “multiple-
30 antenna-port antenna tuner”, having $m = 4$ input ports and n output ports, the multiple-input-port and multiple-output-port tuning unit comprising p adjustable impedance devices, where p is an integer greater than or equal to $2m$, the p adjustable impedance devices being referred to as the “adjustable impedance devices of the tuning unit” and being such that, at the given frequency, each of the adjustable impedance devices of the tuning unit has a reactance, the reactance of any one of the
35 adjustable impedance devices of the tuning unit being adjustable by electrical means, each of the n output ports being indirectly coupled to one and only one of the signal ports through a coaxial transmission line (3); and

m high-power radio-frequency amplifiers (6) which can each deliver 3 MW at the given frequency, each of the high-power radio-frequency amplifiers having an output, the output of said each of the high-power radio-frequency amplifiers being indirectly coupled to one and only one of the m input ports through a coaxial transmission line (5);

the thermonuclear reactor further comprising a signal generation and control unit (7), and being characterized in that:

the signal generation and control unit selects a frequency referred to as the “selected frequency”, in the 35 MHz to 65 MHz frequency range;

the signal generation and control unit adjusts, by electrical means, at least one of the one or more antenna control device parameters, as a function of the selected frequency, by utilizing a lookup table (also spelled “look-up table”);

the signal generation and control unit delivers, to the high-power radio-frequency amplifiers, signals such that the high-power radio-frequency amplifiers are used to apply m excitations to the m input ports, one and only one of the excitations being applied to each of the input ports, each of the excitations being a bandpass signal having a carrier frequency and a complex envelope, the carrier frequency of said each of the excitations being equal to the selected frequency, the m complex envelopes of the m excitations being linearly independent in the set of complex functions of one real variable, regarded as a vector space over the field of complex numbers;

sensing units, which are not shown in Figure 2, are used to sense, at each of m or more places in the ion cyclotron resonance heating system, one or more electrical variables, to obtain “sensing unit output signals”, each of the sensing unit output signals being mainly determined by at least one of the electrical variables sensed at one of said m or more places in the ion cyclotron resonance heating system;

the signal generation and control unit uses one or more of the sensing unit output signals, to activate one or more warning signals if the presence of an edge localized mode is detected in the vacuum chamber of the thermonuclear reactor;

the signal generation and control unit estimates q tuning parameters by utilizing the sensing unit output signals, where q is an integer greater than or equal to m , each of the tuning parameters being a quantity depending on an impedance matrix seen by the output ports; and

the signal generation and control unit adjusts, by electrical means, the reactance of one or more of the adjustable impedance devices of the tuning unit, as a function of the q tuning parameters and as a function of the possible activation of one or more of the one or more warning signals.

The q tuning parameters are sufficient to allow a determination of the impedance matrix seen by the output ports and a determination of an impedance matrix presented by the input ports. The wording “are sufficient to allow a determination of the impedance matrix seen by the

output ports and a determination of an impedance matrix presented by the input ports” does not imply that the impedance matrix seen by the output ports and/or an impedance matrix presented by the input ports are determined, but it is possible that the impedance matrix seen by the output ports and/or an impedance matrix presented by the input ports are determined.

5 The nominal reactance of each of the adjustable impedance devices of the tuning unit is, at a given point in time, determined by the signal generation and control unit as a function of a “tuning unit adjustment instruction”, which is generated inside the signal generation and control unit. A new tuning unit adjustment instruction is generated repeatedly.

The ion cyclotron resonance heating system uses a model-based open-loop control scheme
10 in which, if one of the one or more warning signals is activated, then no new tuning unit adjustment instruction is generated; and if none of the one or more warning signals is activated, then a new tuning unit adjustment instruction is generated periodically and as a function of:

one or more quantities depending on the selected frequency; and
a determination of the impedance matrix seen by the output ports, or any equivalent
15 information (for instance, an admittance matrix seen by the output ports, a scattering matrix seen by the output ports, etc).

In addition, a slower extremum-seeking control algorithm is used to adjust the parameters of the model used by the model-based open-loop control scheme, to obtain a perfect adjustment of the ion cyclotron resonance heating system. This extremum-seeking control algorithm adjusts
20 these model parameters, to get closer to an extremum of a performance variable, the performance variable being a real function of the impedance matrix presented by the input ports, or of any equivalent information. The specialist understands how this extremum-seeking control algorithm can be implemented. The specialist understands that the thermonuclear reactor of the invention implements a very fast and very accurate method for automatically adjusting an ion
25 cyclotron resonance heating system of a thermonuclear reactor.

Thus, there is no need to waste radio-frequency power in loads whenever the adjustment is not correct, and/or to operate the high-power radio-frequency amplifiers at a reduced output power, compared to their theoretical maximum output power. Since the multiple-input-port and multiple-output-port tuning unit is such that it can provide, at said selected frequency, for
30 suitable adjustments of the reactances of the adjustable impedance devices of the tuning unit, a low-loss transfer of power from the input ports to the output ports, it follows that the invention maximizes the power that the ion cyclotron resonance heating system can deliver to the plasma existing in the vacuum chamber of the thermonuclear reactor.

INDICATIONS ON INDUSTRIAL APPLICATIONS

35 In all embodiments described above, the multiple-input-port and multiple-output-port tuning unit has $m = 4$ input ports, but this is not at all a characteristic of the invention. In all embodiments described above, each of the output ports is indirectly coupled to one and only one

of the signal ports through a transmission line, but this is not at all a characteristic of the invention. In all embodiments described above, each of the input ports is indirectly coupled to the output of one and only one radio-frequency amplifier through a transmission line, but this is not at all a characteristic of the invention.

5 The method of the invention is suitable for automatically adjusting an ion cyclotron resonance heating system of a thermonuclear reactor. The thermonuclear reactor may for instance be an experimental thermonuclear reactor, or a thermonuclear reactor of a power station or power plant. Since the invention maximizes the power that the ion cyclotron resonance heating system can deliver to the plasma existing in the vacuum chamber of the thermonuclear
10 reactor, it improves the efficiency of the thermonuclear reactor.

CLAIMS

1. A method for automatically adjusting an ion cyclotron resonance heating system of a thermonuclear reactor, the ion cyclotron resonance heating system comprising a tunable antenna (1) and a multiple-input-port and multiple-output-port tuning unit (4), the tunable antenna having n ports each referred to as “signal port”, where n is an integer greater than or equal to 2, the tunable antenna allowing, at a given frequency, a transfer of power from the n signal ports to an electromagnetic field produced by the tunable antenna in a vacuum chamber (2) of the thermonuclear reactor, the tunable antenna comprising at least one antenna control device having at least one antenna control device parameter, said at least one antenna control device parameter having an effect on one or more characteristics of the tunable antenna, said at least one antenna control device parameter being adjustable by electrical means, the multiple-input-port and multiple-output-port tuning unit having m input ports and n output ports, where m is an integer greater than or equal to 2, the multiple-input-port and multiple-output-port tuning unit comprising p adjustable impedance devices, where p is an integer greater than or equal to m , the p adjustable impedance devices being referred to as the “adjustable impedance devices of the tuning unit” and being such that, at the given frequency, each of the adjustable impedance devices of the tuning unit has a reactance, the reactance of any one of the adjustable impedance devices of the tuning unit being adjustable by electrical means, each of the n output ports being directly or indirectly coupled to one and only one of the signal ports, the method comprising the steps of:
- selecting a frequency referred to as the “selected frequency”;
 - adjusting, by electrical means, at least one of the one or more antenna control device parameters;
 - applying m excitations to the m input ports, one and only one of the excitations being applied to each of the input ports, each of the excitations being a bandpass signal having a carrier frequency and a complex envelope, the carrier frequency of said each of the excitations being equal to the selected frequency, the m complex envelopes of the m excitations being linearly independent in the set of complex functions of one real variable, regarded as a vector space over the field of complex numbers;
 - sensing, at each of m or more places in the ion cyclotron resonance heating system, one or more electrical variables, to obtain “sensing unit output signals”, each of the sensing unit output signals being mainly determined by at least one of the electrical variables sensed at one of said m or more places in the ion cyclotron resonance heating system;
 - estimating q tuning parameters by utilizing the sensing unit output signals, where q is an integer greater than or equal to m , each of the tuning parameters being a quantity depending on an impedance matrix seen by the output ports; and
 - adjusting, by electrical means, the reactance of one or more of the adjustable impedance devices of the tuning unit, as a function of the q tuning parameters.

2. The method of claim 1, wherein an average power of the excitations does not vary over time.
 3. The method of claim 1, further comprising the step of using one or more of the sensing unit output signals, to activate one or more warning signals if the presence of an edge localized mode
5 is suspected in the vacuum chamber of the thermonuclear reactor.
 4. The method of claim 3, wherein an average power of the excitations does not vary over time, if there is no activation of one of the one or more warning signals.
 5. The method of any one of the previous claims, wherein a numerical model is utilized in the step of adjusting, by electrical means, the reactance of one or more of the adjustable impedance
10 devices of the tuning unit, as a function of the q tuning parameters.
 6. A thermonuclear reactor comprising an ion cyclotron resonance heating system, the ion cyclotron resonance heating system comprising:
 - a tunable antenna (1), the tunable antenna having n ports each referred to as “signal port”,
where n is an integer greater than or equal to 2, the tunable antenna allowing, at
15 a given frequency, a transfer of power from the n signal ports to an electromagnetic field produced by the tunable antenna in a vacuum chamber (2) of the thermonuclear reactor, the tunable antenna comprising at least one antenna control device having at least one antenna control device parameter, said at least one antenna control device parameter having an effect on one or more characteristics of the tunable antenna, said
20 at least one antenna control device parameter being adjustable by electrical means; and
 - a multiple-input-port and multiple-output-port tuning unit (4) having m input ports and n output ports, where m is an integer greater than or equal to 2, the multiple-input-port and multiple-output-port tuning unit comprising p adjustable impedance devices,
where p is an integer greater than or equal to m , the p adjustable impedance devices
25 being referred to as the “adjustable impedance devices of the tuning unit” and being such that, at the given frequency, each of the adjustable impedance devices of the tuning unit has a reactance, the reactance of any one of the adjustable impedance devices of the tuning unit being adjustable by electrical means, each of the n output ports being directly or indirectly coupled to one and only one of the signal ports;
- 30 the thermonuclear reactor being characterized in that it further comprises means for:
selecting a frequency referred to as the “selected frequency”;
adjusting, by electrical means, at least one of the one or more antenna control device parameters;
applying m excitations to the m input ports, one and only one of the excitations being
35 applied to each of the input ports, each of the excitations being a bandpass signal

- having a carrier frequency and a complex envelope, the carrier frequency of said each of the excitations being equal to the selected frequency, the m complex envelopes of the m excitations being linearly independent in the set of complex functions of one real variable, regarded as a vector space over the field of complex numbers;
- 5 sensing, at each of m or more places in the ion cyclotron resonance heating system, one or more electrical variables, to obtain “sensing unit output signals”, each of the sensing unit output signals being mainly determined by at least one of the electrical variables sensed at one of said m or more places in the ion cyclotron resonance heating system;
- 10 estimating q tuning parameters by utilizing the sensing unit output signals, where q is an integer greater than or equal to m , each of the tuning parameters being a quantity depending on an impedance matrix seen by the output ports; and
- adjusting, by electrical means, the reactance of one or more of the adjustable impedance devices of the tuning unit, as a function of the q tuning parameters.
7. The thermonuclear reactor of claim 6, wherein an average power of the excitations does not
15 vary over time.
8. The thermonuclear reactor of claim 6, wherein one or more of the sensing unit output signals are used to activate one or more warning signals if the presence of an edge localized mode is suspected in the vacuum chamber of the thermonuclear reactor.
9. The thermonuclear reactor of claim 8, wherein an average power of the excitations does not
20 vary over time, if there is no activation of one of the one or more warning signals.
10. The thermonuclear reactor of any one of the claims 6 to 9, wherein a numerical model is utilized for adjusting, by electrical means, the reactance of one or more of the adjustable impedance devices of the tuning unit, as a function of the q tuning parameters.

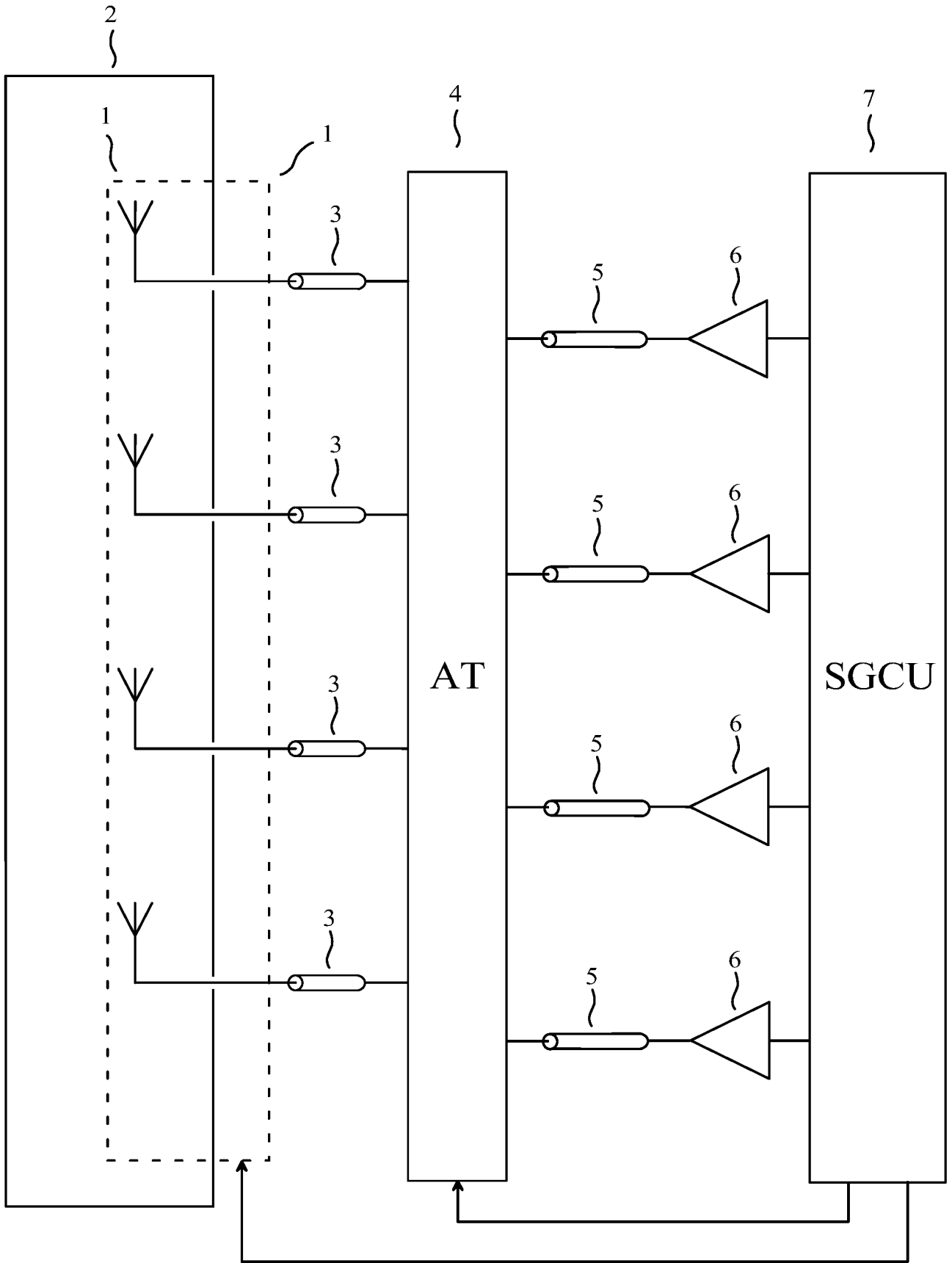


FIG. 1

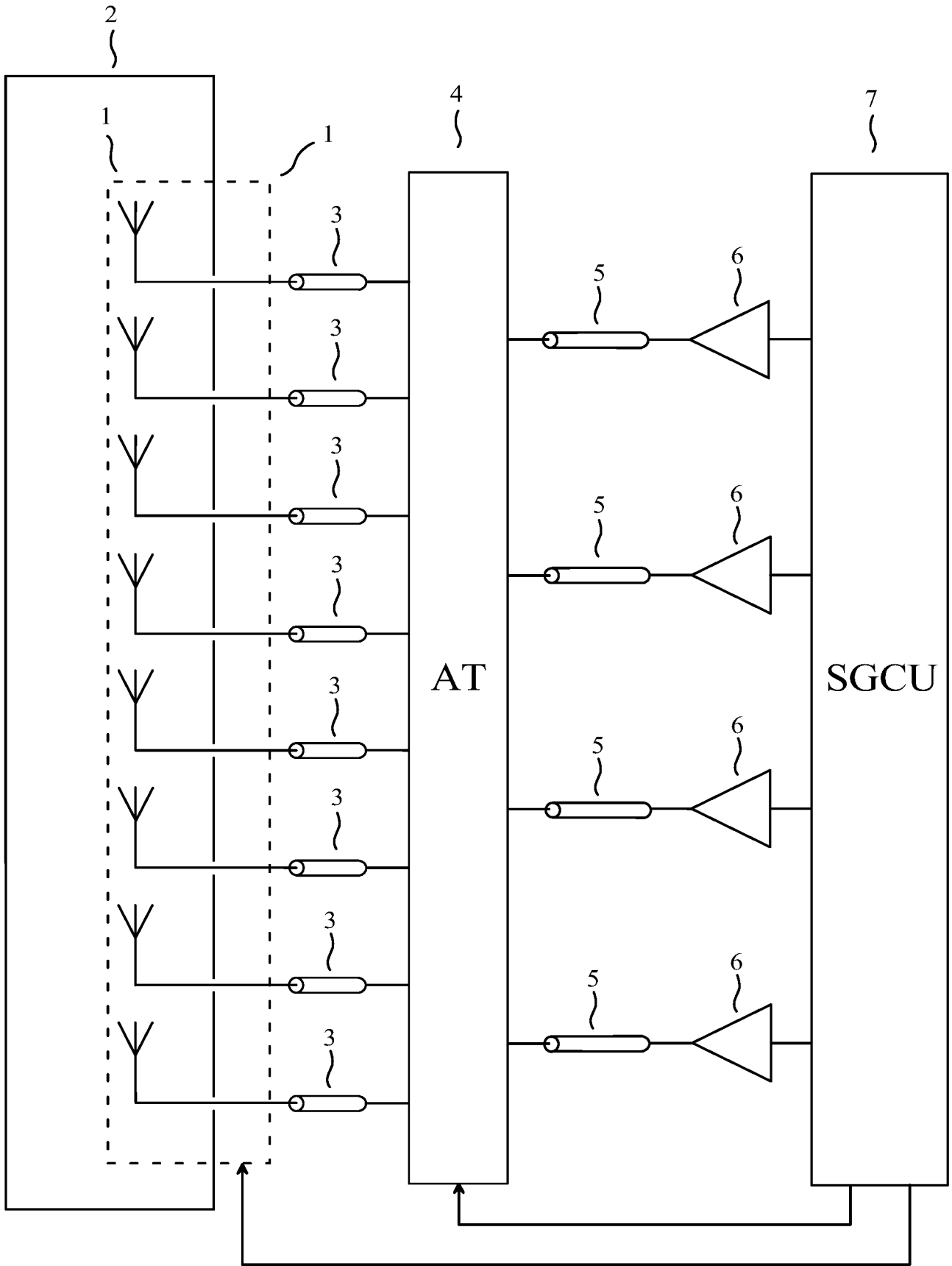


FIG. 2

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2022/054371

A. CLASSIFICATION OF SUBJECT MATTER
INV. H03H7/40 G21B1/11
ADD. H04B1/04

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H03H H04B G21J G21B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, COMPENDEX, INSPEC, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	<p>JOSHI R. ET AL: "Online impedance matching system for ICRH-RF experiments on SST-1 tokamak", FUSION ENGINEERING AND DESIGN</p> <p>, vol. 100 1 November 2015 (2015-11-01), pages 293-300, XP055854915, NL ISSN: 0920-3796, DOI: 10.1016/j.fusengdes.2015.06.095 Retrieved from the Internet: URL:https://www.sciencedirect.com/science/article/pii/S0920379615301241/pdf?md5=cd1c8bd8423038faf9afd81a554cde3c&pid=1-s2.0-S0920379615301241-main.pdf section 3, 4; figures 3, 5</p> <p style="text-align: center;">----- -/--</p>	1-10

Further documents are listed in the continuation of Box C.

See patent family annex.

* Special categories of cited documents :

- "A" document defining the general state of the art which is not considered to be of particular relevance
- "E" earlier application or patent but published on or after the international filing date
- "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- "O" document referring to an oral disclosure, use, exhibition or other means
- "P" document published prior to the international filing date but later than the priority date claimed

- "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- "X" document of particular relevance;: the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- "Y" document of particular relevance;: the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
- "&" document member of the same patent family

Date of the actual completion of the international search

23 August 2022

Date of mailing of the international search report

23/09/2022

Name and mailing address of the ISA/
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Naumann, Olaf

INTERNATIONAL SEARCH REPORT

International application No

PCT/IB2022/054371

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2018/041184 A1 (BROYDE FREDERIC [FR] ET AL) 8 February 2018 (2018-02-08) paragraph [0039] - paragraph [0134] -----	1-10
A	MONAKHOV I ET AL: "ICRH antenna-matrix measurements and plasma coupling characterisation at JET", NUCLEAR FUSION, PUBLISHING SECTION. VIENNA, AT, vol. 58, no. 4, 22 February 2018 (2018-02-22), page 46012, XP020325425, ISSN: 0029-5515, DOI: 10.1088/1741-4326/AAACE3 [retrieved on 2018-02-22] section 3.1, section 3.2, section 7 -----	1-10

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/IB2022/054371

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2018041184 A1	08-02-2018	FR 3053185 A1	29-12-2017
		US 2018041184 A1	08-02-2018
		WO 2017221089 A1	28-12-2017
