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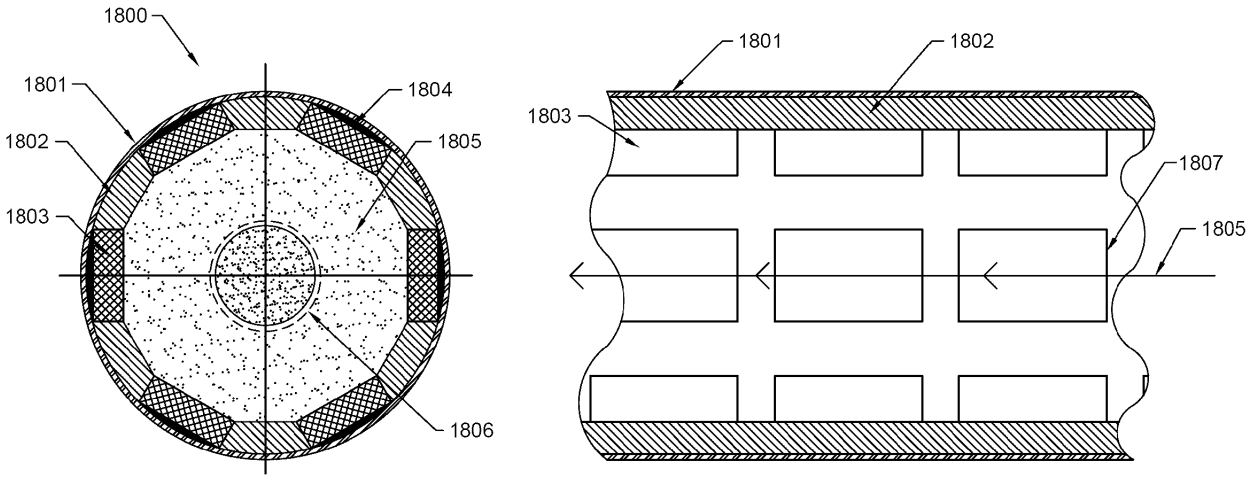
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(54) **A METHOD FOR PRODUCING A PLASMA IN A HEAT CARRIER FOR STABILIZATION OF COMBUSTION AND NEUTRALIZATION OF TOXIC PRODUCTS AND A DEVICE FOR THE SAME**

(57) Present invention relates to a method for producing a plasma in a heat carrier for stabilization of combustion and neutralization of toxic products and a device for the same. According to the method part of heat energy of the heat carrier is converted into a particle beam (CPB&NPB) pulse, said particle beam is accelerated, polarized, focused and deflected back to the area of the heat carrier.

Figure 18

Example of embodiment of ULSIC-device in a toxic neutralization apparatus.



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Description

Technical Field

[0001] Present invention relates to a power engineering and it includes a method and device for creating and heating up a plasma and a conversion of energy.

Background Art

[0002] The disadvantages of the prior art are mainly related to a fact that plasma generation devices are mainly electromechanical devices comprising at least two parts. The first part is a plasma generating apparatus which is built into the combustion chamber and/or reactor of neutralization of toxic combustion products, the second part is an external power source for plasma generation device.

[0003] Drawbacks are related to a need to use specialized electromechanical interfaces between the plasma generator, the power source and the reactor, where the plasma is generated. Representative samples of the prior art are known from the following documents: US2014130980 - "Plasma generation apparatus and plasma generation method"; US2006008043 - "Electromagnetic radiation-initiated plasma reactor, and WO2005017410 - "Plasma catalytic fuel injector for enhanced combustion".

[0004] Another important disadvantages of the prior art are highly specialized and limited applications of such devices, limited embedability and customizability, limited scalability of the architecture of the devices and limited ability to create and heat plasma in large volumes. For example, devices described in documents WO201203013 ("Apparatus for generating pyroelectric crystal neutrons by radiant heat") and US20120170718 ("Apparatus for producing x-rays for use in imaging") make use external electricity for particle beam generation and thermodynamic cycle of pyroelectric and generally are focused on fusion or imaging usages.

[0005] These disadvantages of the prior art limit the wide application of plasma technology in the control of the combustion process and/or neutralization of toxic products, causing difficulties in the design of the various reactors, in particular in terms of production, installation and maintenance, for example, in renovation of obsolete equipment.

Summary of invention

[0006] The aim of the invention is to create so called synchrotron radiation beam with the suitable parameters and which is powerful enough and with suitable spectral composition which will be used as a finely configurable tool for selective ionization of products of combustion, i.e. hot combustion gases that form a heat carrier.

[0007] The synchrotron radiation provides a beam of photons over a wide spectral range - from visible light to hard X-ray. To isolate from the beam photons with desired energy a monochromator is used comprising diffraction gratings and multilayer reflectors.

[0008] The flame is a very complicated phenomenon between the start of combustion of organics to convert it into end-products (in the ideal case - the water and carbon dioxide) that involves thousands of different chemical reactions. For a proper formation of the most efficient and environmentally friendly combustion process is required a thorough study of the intermediate reaction steps.

[0009] Typically for the ionization of the reaction products an electron beam is used, however the particles in the beam do not have sufficiently uniform energy and therefore using a such a beam has its limitations.

[0010] In that sense the synchrotron radiation differs essentially from the electron beam: it can be used for targeted rupture of well-defined chemical bonds within molecules which enable not only to identify chemicals that are formed during combustion, but even to distinguish isomers of the same composition.

[0011] The method and in particular the device according to present invention integrates several physical effects, the main ones are: pyroelectric effect of polar dielectrics, field emission and scattering of electrons, the ionization with a beam of electrons and photons, and the spontaneous emergence of a positive feedback between related processes.

[0012] The device according to invention performs a direct conversion of the thermal energy of the heat carrier into a beam of charged and neutral particles (CPB&NPB) without any electromechanical and/or moving parts, and does not use any additional (external) energy sources. Also the geometric dimension of such a device are compact enabling device to be readily integrated with the reactor/burning chamber.

[0013] Therefore present invention provides a method for producing a plasma in a heat carrier (i.e. hot combustion gases of fuel and oxidant mixture) for stabilization of combustion and neutralization of toxic products, where said method comprising:

a step (a), where part of heat energy of the heat carrier is converted into a particle beam pulse, said particle beam is accelerated, polarized, focused and deflected back to the area of the heat carrier,

a step (b), where in an area of the heat carrier into which said particle beam is directed with said particle beam a highly excited non-equilibrium plasma is generated and heated up for the following initiation of the branching-chain-type plasma-chemical reaction, where in the excited state the plasma retention time is a sum of the single pulse duration of the particle beam and plasma relaxation time up to the beginning of forming of a hot gas to its initial state, where during that time the form of change of the plasma parameters in general follows the pulse shape of the particle beam intensity; and

continually repeating steps above by converting part of heat energy of the heat carrier into beam of electrons and photons to generate and heat up plasma so that heat energy conversion process into particle beam becomes self-sustaining oscillatory process with the positive feedback.

[0014] Preferably said particle beam is a beam of charged and/or neutral particles (CPB&NPB).

[0015] More preferably said particle beam comprising mainly electrons and photons.

[0016] Present invention also provides a device for performing the method described above.

[0017] Therefore present invention provides a device for producing a plasma in a heat carrier for stabilization of combustion and neutralization of toxic products, where said device is embodied as an ultra-large-scale-integrated (ULSIC) device based on cells of multilayer compositions of different linear and nonlinear dielectrics, metals and semimetals on the metal-ceramic surface of the protective sealed hou-sing arranged in connection with the burning chamber.

[0018] In said device part of the heat energy of the heat carrier is set to be converted into a particle beam (CPB&NPB) pulse, said particle beam is set to be accelerated, polarized, focused and deflected back to the area of the heat carrier.

[0019] In an area of the heat carrier into which said particle beam is set to be directed with said particle beam a highly excited non-equilibrium plasma is set to be generated and heated up for the following initiation of the branching-chain-type plasma-chemical reaction, where in the excited state the plasma retention time is a sum of the single pulse duration of the particle beam and plasma relaxation time up to the beginning of forming of a hot gas to its initial state, where during that time the form of change of the plasma parameters in general follows the pulse shape of the particle beam intensity.

[0020] Part of the heat energy of the heat carrier is set to be continuously converted into a particle beam to generate and heat up plasma so that heat energy conversion process into particle beam becomes self-sustaining oscillatory process with the positive feedback, where the housing of the device comprising:

at least at least one output window for the particle beam in connection with the burning chamber, at least one heat conducting surface for heat exchange with at least one heat carrier;

a cell for converting heat energy of heat carrier (i.e. hot gases) generated by burning of a mix of fuel and oxidant into high energy particle beam;

a cell for accelerating, polarising and focusing of the particle beam;

a cell for accelerating, polarising, focusing and deflecting of the particle beam for directing beam into predetermined area of volume of the heat carrier;

a cell for filtering and collimation of output particle beam;

a cell for modulating input heat flux; and

a cell of heat inertia to form a pulse of an input heat flux.

[0021] Preferably said window of output particle beam is comprising at least a cell of filtering and collimation of particle beam, said cell comprising in turn at least one set of multi-layered metal films, comprising collimation layer of thick film and/or foil containing micro-holes (perforation).

[0022] Preferably said heat conducting surface comprising at least a cell of thermal inertia which in turn comprises at least one set of multi-layered metal-ceramic structure.

[0023] Preferably said cell is in thermal contact with at least one cell for modulating input heat flux, where said cell in turn comprising multi-layered metal-ceramic structure comprising a set of ferroelectrics with electrocaloric effect and ferroelectric thin films based on a substrate of a pyroelectric.

[0024] Preferably said device comprises at least a cell for converting heat energy into the particle beam, where said cell having a vertically-pillar or planar or mixed internal structure.

[0025] Preferably said cell comprises at least one cell of heat flux modulation.

[0026] Preferably said cell includes at least one multilayer stack of pyroelectrics, emission targets, pre-accelerator and polarizer of particles, multilayer reflectors, conductors and dielectrics.

[0027] Preferably said device includes at least one pyroelectric stack comprising array of single or different materials having different phase transition temperatures for broadening range of operating temperatures and having different surface shapes and with different surface coating materials.

[0028] Preferably said pre-accelerator and polarizer of particles comprise at least one array of stacks of pyroelectric materials and having different surface shapes and with different surface coating materials.

[0029] Preferably said multi-layered reflectors are in the form of surface coatings and/or dielectric substrates of structural elements.

[0030] Preferably said device comprises at one cell for accelerating, polarising and focusing of the particle beam in a tangential electrostatic field said cell consisting of array of pyroelectric stacks.

[0031] Preferably said device comprises at one cell for accelerating, polarising, focusing and deflecting of the particle beam in tangential electrostatic and magnetic fields, said cell consisting of composite array of pyroelectric stacks and magneto-electric/multiferroic materials.

[0032] Most preferably said device has scalable single design for different of output radiant power and operating temperatures.

Brief description of drawings

[0033] The present invention is now described in greater detail with references to the accompanying drawings, in which:

Figure 1: a brief schematic representation of the order of disclosure;
Figure 2: a schematic of spontaneous polarization (PS) process of polar dielectrics due to temperature gradient;
Figure 3: a schematic of dynamical pyroelectric response to temperature changes;
Figure 4: a schematic of dynamical pyroelectric (+ an adjoining medium or target) response, giving off pulsewise radiant flux to temperature changes;
Figure 5: a schematic of thermal positive feedback between a pyroelectric and its generated plasma through energy-exchange;
Figure 6: a flowchart of one among many architectural solution of ULSIC-device, depending on application;
Figure 7: a schematic of components and spatial relationships between parts (items) into PE stack;
Figure 8: a schematic of quasi-equivalent transformations of a bulk and/or film pyroelectric (PE) item into planar capacitor and dipole model;
Figure 9: a schematic of PE stack geometry;
Figure 10: a schematic of PE stack design;
Figure 11: a schematic of manipulation useful properties of different ferroelectric by using electrostatic field;
Figure 12: a schematic of spatial relationships between reflectors and other parts of CPB&NPB cell;
Figure 13: a schematic of components and spatial relationships between parts of CPB&NPB cell. Options A and B;
Figure 14: a schematic of one among many options a bulk, spatial configurations and component parts of xyz deflecting cell;
Figure 15: a schematic of design options of CPB&NPB stack;
Figure 16: a schematic of model chip housings and built-in-place CPB&NPB stacks;
Figure 17: an example of embodiment of ULSIC-device in a hydrogen power cell for micro-CHP apparatus;
Figure 18 an Example of embodiment of ULSIC-device in a toxic neutralization apparatus;
Figure 19: a schematic of installation options of ULSIC-devices in various environments;
Figure 20: a schematic of design options of ULSIC-devices, and relevant applications.

Description of embodiments

[0034] The present invention has been described and illustrated in detail with references to the accompanying drawings. However, the present invention is not limited to the embodiments described above nor illustrated in the accompanying drawings. There are other possible embodiments and combination of characteristic features which can be derived and implemented on the basis of the present description and accompanying claims.

[0035] At least one exemplary embodiment of the present invention is disclosed herein. It is understood that modifications, substitutions and alternatives are apparent to those skilled in the art and may be made without departing from the spirit and scope of this disclosure. This description is intended to cover any device or variants of an exemplary embodiment(s). Furthermore, in this specification, the terms "comprise" or "comprising" or "include" or "including" does not exclude other elements or steps, the terms "one" or "single" does not exclude a plurality, and the term "and/or" means that either or both. Furthermore features or steps which have been described can also be used in combination with other features or steps and in any order, unless the description or context suggests otherwise.

[0036] For the purpose of better understanding of the invention and its embodiments, first are given explanations of the physical effects and phenomena upon which the present invention is based on.

The Pyroelectric Effect

[0037] Raising or lowering the temperature of the polar dielectric/pyroelectric changes in them the intensity of the

thermal motion of the particles, the polar orientation of the complexes, and the distance between them, leading to a change in the spontaneous polarization of $dP\ s = \gamma dT$, where γ is the pyroelectric coefficient, dT is the change of temperature, where heating and cooling consist virtually reversible thermodynamic cycle. Consequently, on the surface of the pyroelectric material occur uncompensated electrical charges $dq = dP\ s \cdot S$ and potential $d\varphi = dq/C$, where S is the surface area of a pyroelectric material and C is the electric capacitance of a pyroelectric material.

[0038] Figure 2 depicts a pyroelectric effect scheme involving spontaneous polarization due to the temperature gradient. The pyroelectric coefficient γ reaches a maximum value near the point (the Curie temperature T_C) where second order phase change occurs.

[0039] The electric field strength $|\bar{E}|$ may exceed 10^9 V·cm^{-1} depending on the chemical composition and the crystal lattice structure, scale factor, the volume and surface shape of a pyroelectric material and thermal conditions (temperature). Figure 3 depicts a the dynamic response diagram of pyroelectric material a response to a temperature changes.

[0040] The performance indicator of a pyroelectric material in general can be represented as $FOM = \gamma(T) / \varepsilon\varepsilon_o C\ v \cong \gamma / \varepsilon\varepsilon_o C\ v$, where ε and ε_o are respectively the relative permittivity of a pyroelectric material and the vacuum permittivity, $C\ v$ is the volumetric heat capacity of a pyroelectric material.

Field emission and scattering of electrons

[0041] The electrical field strength ($E \sim 10_7$ - 10_8 V·cm-1) which relates to a temperature change of a pyroelectric material, causes field emission of electrons (the Schottky effect) with energies of the order of 10^{-1} - 10^3 keV and above depending on the Z target (atomic number) and the emission current
$j \sim E_2$ ($j \leq 10_8$ A·cm-1) or E 3/2 ($j > 10_8$ A·cm-1). Electrons are emitted from the inner shells of atoms, forming shell vacancies that are unstable excited state of the atom. Transition of atoms into a stable state is accompanied by the transition of electrons from the outer shells into the inner shells accompanied with the emission of characteristic X-radiation, where the energy of said radiation is equal to the difference between energies of said shells. Photons of X-ray bremsstrahlung are produced in the process of scattering of electrons in an electric field of atomic nuclei. Figure 4 depicts the dynamic response diagram of pyroelectric, showing flow of electrons and photons as response to a temperature change.

Ionization with a beam of electrons and photons

[0042] Ionization with a beam of electrons and photons with energies of the order of 10^{-1} to 10^3 keV and above. The plasma is created by the ionization of the following channels: electron-impact ionization by the beam of electrons, photoresonance and multiphoton ionization.

Positive feedback

[0043] It is known that the temperature change in the plasma under the action of high-energy beam of electrons and photons, relates primarily to the deceleration and absorption processes. During deceleration, only about 1 % of the kinetic energy of the electron goes to X-rays, 99% of the energy is converted into heat. Figure 5 is a diagram of a thermal positive feedback between the pyroelectric and the plasma created by it through the energy exchange process.

[0044] Figure 5 depicts the thermodynamic cycle of a pyroelectric unit. The cycle is formed by the influence of the pulse of thermal flux Φ_T^*, where t_T^* is pulse duration, wherein the front and trailing edges of the pulse correspond to the heating and cooling. With delay t_1 = n·sec (time transients in a pyroelectric unit for charge storage and achieve an electric potential required for field emission), is formed the pulse of particle flux Φ_E , where $t_E \approx t_T^*$ is pulse duration, that creates and heats up a plasma. The particle flux pulse characteristics (shape, duration, period, and duty cycle) are repeated in the thermal flux pulse characteristics that plasma is radiated, i.e. a time of ionizing event t_2 and plasma relaxation lasts a few μ sec in contrast to particle flux pulse duration t_E a few sec. In case of plasma IR-radiation as a point light, the part of heat flux radiated by a plasma falls on the surface area S of a pyroelectric: $\Phi_T^* \approx \Phi_T \cdot S/4\text{-}\pi R^2$, where R is distance to surface S, and the cycle repeats. In case of free cooling of a pyroelectric (a time of thermal relaxation t_{relax}), criteria for the processes synchronization and the stability of the feedback is:

$$\begin{cases} t_T^* \cong t_E \cong t_T \cong 2 \cdot t_{relax}; \\ t_1 \cong \frac{1}{2} \cdot t_T^* \cong t_{relax}; \\ t_3 \geq 2 \cdot t_{relax}; \\ t_{period} = t_1 + t_3 \geq 3 \cdot t_{relax} \end{cases},$$

where *tperiodis* the pulse period.

[0045] Below is described a conversion apparatus for converting part of the combustion heat energy (usually lost in the form of heat and not used) into a beam of charged and/or neutral particles in order to create and heat up a plasma to stabilize combustion and/or to neutralize toxic wastes.

[0046] The device is embodied as an ultra-large-scale integrated (ULSIC) device based on cells of multilayer compositions of different linear and nonlinear dielectrics, metals and semimetals on the metal-ceramic surface of the protective sealed housing arranged in connection with the burning chamber, said housing comprising at least one output window for the particle beam in connection with the burning chamber, at least one heat conducting surface for heat exchange with at least one heat carrier.

[0047] Figure 6 depicts a block diagram of one of the possible architectural embodiment of the ULSIC-device. The device is a highly integrated device comprising at least one or several stacks layers (CPB&NPB stack 601), where each stack comprises at least one functional cell or several functional cells of different functionality:

protective sealed housing with interfaces 600; a cell for converting heat energy of heat carrier into the particle beam (CPB&NPB cell 602); a cell for accelerating, polarising and focusing of the particle beam (AFPB cell 603); a cell for deflecting of the particle beam (DPB cell 604); a set of different Bragg's reflectors 605; a bandpass filter and collimator array 606; a cell for temperature modulation (TM cell 606); and optionally with input bandpass filter and thermal inertia unit 607, a logical unit 608, the thermoelectric module 609 based on the Seebeck or Peltier effect and heatsink 610.

[0048] The architectural embodiment of the device can either be predefined (a set of similar plasma generator ULSIC-devices according to present invention described herein) or customized according to the following criteria: a working environment (corrosiveness of environment, vacuum, normal or elevated pressure); chemical composition of the fuel and oxidant, for example, hydrogen and oxygen, methane and air, etc.; a specific (precise) operating temperature range; power and frequency band (wavelength) of radiation, for example, to focus on the selective ionization of single-type molecules, atoms, or excitation of nuclear oscillations or inner-shell electrons; a specific form-factor (housing geometry and dimension); and etc.

[0049] The key elements of the above cells is a pyroelectric stack (PE stack) volumetric 700 and/or layered film 701 structure of series-parallel connected pyroelectric materials, conductors and insulators 702, see Figure 7(a). The pillar design 703 is more preferred for stacked crystal bars (eg. an accelerator-polarizer and/or a deflector of particles) in contrast, multilayer structure 705 like a sandwich based on a substrate 706, is preferred for reflectors and/or a specific target-reflector. The planar design 704, comprising of stacked bars between ceramic substrate-based ferroelectric/multiferroic thick films, is suitable to use the magnetoelectric and electrocaloric effects.

[0050] Depending on the application, PE stack structure 700, 701 may include pyroelectrics with various physico-chemical parameters 702 and thus efficiently operate over a wide temperature range, for example, a hydrogen power cell needs a special ULSIC-device with operating temperature range of 900-1500K in contrast, toxin neutralization apparatus operates in the range of 500-900K. In this case, one of the basic design limits of the stack is the melting temperature (T_M) of any pyroelectric materials which must be greater than the temperature of second order phase transition temperature (T_C) of any other pyroelectric in the stack and accordingly higher than the maximum operating temperature (T_{OP}) of the PE stack ($T_{OP} \sim T_C << T_M$), see Figure 7(b).

[0051] Second important aspect is that the maximum value of the pyroelectric coefficient $\max_{T_C-\Delta T \le T < T_C}\left(\frac{d\gamma}{dT}\right)$, is achieved in a relatively narrow range of temperature change $\Delta T \cdot 707$, its enables the possibility to control the direction of polarization vector through temperature modulation in this temperature range and thus increase the efficiency of converting thermal energy into electrical energy.

[0052] Evaluation of the efficiency of the thermoelectric conversion coefficient K_{TE} of a pyroelectric (without considering the piezoelectric effect) using quasistatic ratio obtained based on the Gibbs thermodynamic potential, can be expressed as $K_{TE}^2 = dW_E / dW_T \cong \gamma^2 T_{op} / \varepsilon\varepsilon_0 C_V$ where W_T and W_E are respectively total heat energy and produced electric energy, ε and ε_0 are respectively the relative permittivity of a pyroelectric material and the vacuum permittivity and C_v is the volumetric heat capacity of a pyroelectric.

[0053] The thermoelectric conversion coefficient K for a cascade of N pyroelectrics:

$$K = \sum_{i=1}^{N} K_{TE,i}^2 = \sum_{i=1}^{N} \gamma_i^2 T_{op,i} / \varepsilon_i \varepsilon_o C_{V,i}$$

[0054] For example, for a crystal of lithium tantalate ($LiTaO_3$)

$$\lim_{T_{OP} \to T_C} K_{TE} \approx 23\%.$$

[0055] Thus, one of the main criteria for design of the PE stack is to maximize the efficiency of thermoelectric conversion of an individual pyroelectric and a pyroelectric stack as a whole under the above temperature limits.

[0056] Figure 8. As an auxiliary tool for calculating electrical steady-state characteristics of the PE stack can be used a quasi-equivalent representation of a pyroelectric 800 and stack in the form of a parallel-plane capacitor (without self-impedance) 801 and electric dipole 804. Simulation by capacitors is used for calculating the surface charge q and the electric potential φ of series-parallel connected pyroelectrics, where serial connection 802 maximizes a potential φ,

$$\frac{1}{C} = \sum_{i=1}^{N} \frac{\varphi_i}{q} = \sum_{i=1}^{N} \frac{1}{C_i}$$

in contrast, parallel connection 803 maximizes a charge q,

$$C = \sum_{i=1}^{N} \frac{q_i}{\varphi} = \sum_{i=1}^{N} C_i$$

[0057] Simulation by dipoles 804 is used for calculating the electrical field strength $|E_D| = 2 \cdot q / 4\pi\varepsilon_0\varepsilon m \cdot r\,2$ at a certain point $r^2 >> d^2$ of a medium with the relative permittivity εm and its configuration, for example, the strength of quasiuniform electric field at midpoint r between two oppositely charged pyroelectrics 805 is $|E_{2D}| = 4 \cdot q / 4\pi\varepsilon_0\varepsilon m \cdot r2$, and for acceleration of charged particles by the tangential electric field is used several paralleled pyroelectrics, in case a pair 806 of equal charges, the axial strength therebetween can be valued as

$$|E| = 2\sqrt{|E_+|^2 + |E_-|^2 - 2|E_+| \cdot |E_-| \cdot \cos(\alpha)}$$

where α is the angle between $E+$ and $E-$ vectors one of dipoles in same axial point 807.

[0058] Geometric form of the PE stack depends on the functional purpose of the cell in which the stack is used. Different shape of surfaces S of the PE stack, such as: flat 900, cone-type 901, parabolic 903 and periodical structure 904, causes uneven volumetric and surface charge distribution $\sigma = dq/dS$ and, as a result, different configurations (i.e. the change of field symmetry) and intensity of the electrostatic field around the surfaces of the stack, this allows to use PE stacks for amplifying and focusing, polarization, modulation and deflection of the particle beam, for example, AFPB, DPB and TM cells, see Figure 9(a-c).

[0059] The use of various types of coatings 906 on the interface of the PE stack (polished without coating 905) enables additional opportunities to form parameters of the beam. Single-layer 907 (a mesh 908) and/or multilayer thin metal films 909 act as combined target-reflector (eg, CPB&NPB cell). Field emitter arrays like Spindt-type arrays, such as: micro- and nanometric cone 910, tube 911 and rods 912, reduce the emission potential and form coherent e-beam, see Figure 9(d).

[0060] Figure 10 depicts a schematically a selection of the PE stack design depending of its functional purpose 1000. The PE stack 1001 is the key element that converts heat flux in symmetrical electrostatic field 1002. The field 1002 of the stack 1001 by using materials with different physical phenomena and effects, is transformed into particle flux 1003, asymmetrical electrostatic field 1004, magnetic field 1005 and thermal field 1006 with gradient ∇T. These generated fields have the practical properties, such as: acceleration 1007, focusing 1008, polarization 1009 and deflection 1010 of particles and thermo-modulation 1011, and are embodied in finite functional cells. There are CPB&NPB cell 1012, AFPB cell 1013, DPB cell 1014 and TM 1015, and combinations of which are embodied in CPB&NPB stack 1016 and plasma generator 1017.

[0061] The cell 1012 operates like an e-beam microgun based on thermo pumping and the field emission, and its comprises: array of stacks 1001; emission targets; at least one preaccelerator and polarizer of particles; at least one multilayer reflector; at least one dielectric substrate.

[0062] The emission of electrons and photons from the target takes place under the influence of electrostatic field $\overline{E}$ of array of stacks 1001. Evaluation of the emission current density can be represented by a simplified conventional Fowler-Nordheim equation:

$$j \approx 1.54 \cdot 10^{-6} \cdot \frac{\left|\overline{E}\right|^2}{\Phi} \cdot \exp\left(-6.83 \cdot 10^{7} \cdot \frac{\Phi^{2/3}}{\left|\overline{E}\right|} \cdot \Theta(y) \right)$$

where tabulated values are: Φ- electronic work function; $\Theta(y)$ - Nordheim function.

[0063] The spectrum of the bremsstrahlung photons is continuous, and it depends of the electric potential φ and Z targets. In contrast, the characteristic of X-ray spectrum is a line spectrum with a high degree of monochromaticity (monochromaticity depends on Z targets). The wave bandwidth λ limits of the energy spectrum of the photons of the bremsstrahlung and the characteristic radiation can be estimated as:

$$\lambda = \begin{cases} \dfrac{2\pi\hbar c}{e\varphi}, \textit{lower lirnit of the continuum} \\ \left(R_Y (Z-\sigma)^2 \left(\dfrac{1}{n^2} - \dfrac{1}{k^2} \right) \right)^{-1}, \textit{Moseley law} \end{cases}$$

where *h* is Planck's constant, c is the speed of light, e is the charge of the electron, *Ryis* Rydberg's constant, σ the screening constant, *n* is a shell number on which the electron has been moved to, *k* is a shell number from which the electron has been moved ($K\alpha$, $K\beta$, $L\alpha$, $L\beta$, values used in practice, Φe, $\beta \approx 25\%$ Φe, α).

[0064] Integral photon flux of radiation that are emitted by the targets can be estimated by the semi-empirical formula in the following form:

$$\Phi_e = \Phi_e^{Brk} + \Phi_e^{Chr} \approx kZj\varphi^2 + \sum_K \Phi_e^{Chr} + \sum_L \Phi_e^{Chr}$$

where Φ e Brk and Φ e Chr are respectively bremsstrahlung radiation flux and characteristic radiation flux, *k* is a specific factor ($\sim 10^{-8}$-10^{-9} $\cdot V^{-1}$).

[0065] The criterion for choosing a design, a geometry and materials of targets is a pre-designed value of the wave bandwidth λ (or frequency band v=c/λ) of the beam and emission capability of materials.

[0066] The design of the cells 1012 provides the ability to use additional PE stack array as a preaccelerator of particles due to the tangential electrostatic field (eg, for *e* -, $|E|$ = n·kV/cm ~*e* - =*e* - + n·keV, travel time for 1 cm ~ 10^{-10} sec), also when the preaccelerator polarizes and focuses the particle beam on the target.

[0067] Polarization of the particle beam can occur by the electrostatic field and also by the magnetic field when on top and/or between parts of the PE stack 1100 is added of one or more layers of ferroelectric/multiferroic films 1101 for generation of the magnetic field based on the magnetoelectric effect, see Figure 11 (a). The magnetoelectric effect in ferroelectric/multiferroic takes place under the influence of electrostatic field $\overline{E} \sim 10^5 Vcm^{-1}$, leading to magnetic polarization $\overline{P}$ and inducing the magnetization $\overline{M} = \frac{\mu}{4\pi}\overline{E}$, where μ is the magnetoelectric factor (tensor) of material, and magnetic field $\overline{H}$. The chart 1102 illustrates the magnetization $\overline{M}$ of layer 1101, where $\ominus$- flip angle, i.e. the angle to which the magnetization $\overline{M}$ is rotated relative to the main magnetic field direction by the application of field $\overline{E}$. The chart 1103 illustrates dependence of magnetization $\overline{M}$ against electric field $\overline{E}$.

[0068] Depending on the application and the spatial arrangement of parts CPB&NPB cell can include a thin film multilayer reflector/reflectors 1200 made of n pairs 1201 of different dielectrics, metals and/or their composition, see Figure 12(a). The criterion for the choice of materials, design and spatial arrangement of reflector/reflectors is the fulfilment of the Wulff-Bragg's condition (Bragg's law), pre-designed wavelength λ of incident beam 1202 at grazing angle Θ and reflected beam 1203 and the polar radiation pattern of the radiation. The chart 1204 illustrates typical dependence of a reflectance of a matter against a wavelength of an incident beam.

[0069] As described above, a target-reflector 1205 may be disposed on the surface of the PE stack 1206 based on the substrate 1207, or it can be part of the substrate coating 1208 and/or PE stack 1209 (preaccelerator-reflector) and/or

the substrate 1210 itself of the CPB&NPB cell, see Figure 12(b).

[0070] Embodiments of the CPB&NPB cell 1300 comprising of an array of PE stacks 1301, emission targets 1302, preaccelerator 1303 and reflectors 1304 is shown on Figure 13. Simple structure 1305 of the cell 1300 comprises substrate-based 1304 stack 1301 that is connected to wedge-type target 1302 with facet at a slope of 40-45 degrees relative to the stack. More complex structure of the CPB&NPB cell 1308 is based on an array of four stacks 1307 and may include a target 1302, also at least one preaccelerator 1303 based on two stacks 1301. The array 1307 is based on either a substrate with a strip-reflector 1309 or without it 1310.

[0071] Other functional units of the CPB&NPB stack is AFPB cell for accelerating, polarizing and focusing of particle beam and DPB cell for beam deflection. Structurally these cells are have little difference from each other and they form an array 1400 of *N* PE stacks 1401, and they are arranged around the beam axis 1402 so that both tangents to the beam path and the electric field vector are parallel to each other in the same coordinate points along the path of the beam through the cell, see Figure 14.

[0072] The deflection angle (α, β, γ in relative to coordinate axes) of charged particles occurs by the influence of asymmetric electric and/or magnetic field of the array 1400, thus the control actions for asymmetry adjustment and deflection angle are:

$$\overline{E} = \sum_{i=1}^{N} \overline{E}_i$$

where $\overline{E}i$ the electrostatic field of *i*-th stack 1401 and, the deflection angle is

$$\begin{pmatrix} \tan\alpha \sim \left|\overline{\mathrm{E}}\right|_X \cdot \left|\overline{v}_0\right|_X^{-2} \\ \tan\beta \sim \left|\overline{\mathrm{E}}\right|_Y \cdot \left|\overline{v}_0\right|_Y^{-2} \\ \tan\gamma \sim \left|\overline{\mathrm{E}}\right|_Z \cdot \left|\overline{v}_0\right|_Z^{-2} \end{pmatrix}$$

where $|\overline{v}_0|_{axis}$ is the projection of the velocity vector of particle beam on axes X, Y, Z, and therefore the control values of degree symmetry of $\overline{E}$ are depended on $\overline{E}_i(\sigma,x,y,z)$, where σ the surface charge, *y* the length of stack 1401, *x* and *z* the distance to axes X, Z (if all stacks 1401 have the same field $\overline{E}_i$, it is an accelerator), also true for $|\overline{H}| \propto \overline{M} \Leftrightarrow \overline{E}$. The main difference of materials and geometrical shapes of PE stacks 1401 in cells was described above.

[0073] As mentioned above, the maximum efficiency of thermoelectric conversion ($K_{TE} \sim \gamma/\varepsilon_o\varepsilon$) is achieved near the phase transition point (Curie temperature, T_C), thus the operating mode of harmonic temperature oscillations near that point is most preferred mode. The functional element of the inverse transform of the electric field in the temperature based on electrocaloric effect, embodied in a temperature modulation cell (TM cell).

[0074] Under the influence of the electric field $\overline{E}$ the vector of the polarization of a ferroelectric $\overline{P} \neq 0$, $P^2 \sim E^{2/3} \sim \Delta T_{which}$ reduces the entropy $S|_{E=0} > S|_{E\neq 0}$ under adiabatic conditions *TdS=0,* leads to an increase in temperature. When the field switches off (more profitable is to change the polarity of the field which increases the lifetime of a ferroelectric), the entropy increases and the temperature drops. For example, thin film of $PbZr_{0.95}Ti_{0.05}O_3$ generates $\Delta T \approx 12K$, $\Delta E \sim 10^5$-$10^6 V \cdot cm^{-1}$. The chart 1104 in Figure 11 (b) illustrates the dependence of temperature change (ΔT) of the ferroelectric against switched electric field $\overline{E}$. The chart 1105 shows the deployment of ferroelectric-hysteresis loop into heating-cooling process 1106 of flowing in time. The chart 1107 depicts the nonlinear dependence of $\gamma/\varepsilon_o\varepsilon$ against temperature near second-order transition point.

[0075] Simple structure of the CPB&NPB stack 1500 may comprise at least one CPB&NPB cell 1501, at least one AFPB cell 1502 and/or at least one DPB cell 1503. The cell 1502 and/or cell 1503 may also part of the CPB&NPB multistage stack 1504 and to carry out an independent role, for example, to collect and focus the beams from several stacks 1500 in one beam 1505, see Figure 15.

[0076] Depending on the application, the total amount of CPB&NPB stacks in ULSIC plasma generator may vary from one to several units.

[0077] It was mentioned above that the plasma generating device has a predefined and/or a customized structure, in particular, it has a protective sealed housing. Figure 16 depicts a different embodiments of the housing, such as a rectangular 1600 and convex 6 and/or 8-gon 1601, and placement of CPB&NPB stacks 1605 in them, such as packed in dielectric square-cell honeycomb 1610 or placed on substrate 1612 a planar array 1611.

[0078] As can be seen from Figure 16(a), surface 1602 of the device is an interface in which there is a window 1603,

through which particle beam is transmitted to exposure object. The main criterion for selecting the material and thickness of window 1603 of the interface 1602 can by present as (in the case of monatomic substances):

$$d \le -\ln\left(\frac{\Phi_e}{\Phi_{e,0}}\right) / \mu,\ \mu = \left(\rho, Z, E_{photon}\right)$$

where d is a window thickness, $\mu=\tau+\sigma+\chi$ *is* a linear absorption coefficient, and where tabulated values for substances: T is the linear attenuation coefficient due to photoeffect, σ is the linear attenuation coefficient due to Compton effect, X is the linear attenuation coefficient due to electron-positron pair.

[0079] Depending on the application, the above described window 1603 of the interface 1602 which is formed as a multilayer film structure (or a multilayer metal foil structure of different metals), can act as a bandpass filter, the characteristics of which are defined by relation $\mu i = \tau i + \sigma i + \chi i$ for *i*-th (*i*- number of film) film material, i.e. which weakening effect will prevail in a particular *i*-th film layer and which 10 waveband λ will be suppressed, for example, selective ionization of single-type molecules by strictly determined frequency (wavelength) for toxic waste neutralization.

[0080] Depending on the application, the interface window 1603 is formed as a multilayer structure which may include a layer consisting of a collimation matrix 1604 for obtaining a quasi-parallel beam and limiting the spatial cross section of the particle beam. In this case, the matrix is placed over the array of CPB&NPB stacks 1605.

[0081] Depending on the application, ULSICs plasma generator may comprise optoelectronic devices 1606 and/or logical control unit 1607, in this case the source of electrical energy for their operation may be integrated with a thermoelectric converter device 1608 based on Seebeck and/or Peltier effect.

[0082] The heat transfer between the heat source and the device may be through a direct contact heat transfer and infrared radiation and convection.

[0083] For interaction of ULSIC plasma generator with a heat carrier, the device comprises the interface layers 1602 and 1609. These interfaces allow due to the contact surfaces to ensure good thermal contact between the device and the heat carrier. The selection criteria of interface material are high thermal conductivity and compatibility with environmental conditions (eg, based on nickel-ferrous-Me alloy with protected coating either alumina or nitride ceramics, etc.).

[0084] In direct contact with the interface can be the cell of thermal inertia which generates pulse (pulse delay time and latency and duty cycle) of the input heat flux from the heat source. Pulse parameters, in turn, are crucial parameters for the positive feedback between the device and the heat carrier, see Figure 5.

[0085] There are two ways implementing a mechanism of thermal inertia for obtaining required timing pulses of heat flux, either by the variation of materials with different thermal resistance, or by the use of thermodynamic characteristics of materials according to their phase transition temperatures.

[0086] Figure 17 depicts embodiment of ULSIC-device in a part of hydrogen power cell 1700 for micro combined heat and power (micro-CHP) apparatus. ULSIC-devices 1702 are installed inside the vacuum chamber 1701 and opposite the combustors 1703, which burn a hydrogen-oxygen mixture, where 1706 is flow direction. IR radiation 1709 of hot gases of the torch 1705, including formed steam is transmitted to ULSIC-devices, which convert heat into CPB&NPB flux 1710 that is directed back to ionize the gases, and finally creates and heats up a plasma. A leader shows a part axial-section of the device, consisting of a housing (eg. alumina) 1714, CPB&NPB 1715 and TM 1713 cells, and a window 1711 with collimator matrix 1712 (eg. silicon nitride or pure silicon is suitable too, and aluminum respectively). Also, in top 1707 of combustors is inputted a reheat steam 1708, which mixed with the main flow of combustion gases, and mixture heated up to state of superheated steam.

[0087] Figure 18 illustrates an example of application of ULSIC-device in an apparatus of waste neutralization 1800, comprising of the chamber 1801 with inside coating that is a mosaic of zirconia-based ceramic 1802 and a set 1807 of the devices 1803, where 1804 is an adhesive. The device 1803 converts heat energy of waste flux 1805 (i.e. hot gases, steams and/or liquids, where 1806 is an input) into a photon beam that is directed back to waste flux, and has a fine-tune to a specific energy of molecular bonds and atom-bond electrons. Photochemical degradation of a specific molecular and/or intra-atomic bonds creates conditions for a new bonding and chemical reactions, as required. As mentioned above, a fine-tune to a specific energy depends on Z target and characteristics of collimator matrix that defined on pre-design stage.

[0088] ULSICs plasma generator 1900 has a sealed housing and depending on the application it can be used in various corrosive environments 1904 (hot gases/plasma) and under different pressures, see Figure 19. Installation of the device is carried out by means of adhesive and/or a special clip-clamping 1901 that does not violate the integrity of the surface to which the device is attached to (a wall 1902). Figure 19 shows three possible positions (A, B, C) in relation to the burning or neutralizing reactor 1903.

[0089] Figure 20 illustrate exemplary embodiments, but the present inventions is not limited there to. This schematic shows a design options of ULSIC devices, and relevant applications.

[0090] For person skilled in the art it is obvious that the present invention is not limited to the embodiments depicted in the attached drawings and described above, but within the scope of attached claims many other embodiments are possible.

Claims

1. A method for producing a plasma in a heat carrier for stabilization of combus-tion and neutralization of toxic products, said method comprising steps ***characterized by***
a step (a), where part of heat energy of the heat carrier is converted into a particle beam (CPB&NPB) pulse, said particle beam is accelerated, polarized, focused and deflected back to the area of the heat carrier,
a step (b), where in an area of the heat carrier into which said particle beam is directed with said particle beam a highly excited non-equilibrium plasma is generated and heated up for the following initiation of the branching-chain-type plasma-chemical reaction, where in the excited state the plasma retention time is a sum of the single pulse duration of the particle beam and plasma relaxation time up to the beginning of forming of a hot gas to its initial state, where during that time the form of change of the plasma parameters in general follows the pulse shape of the particle beam intensity, and
continually repeating steps above by converting part of heat energy of the heat carrier into a particle beam to generate and heat up plasma so that heat energy conversion process into particle beam becomes self-sustaining oscillatory process with the positive feedback.

2. The method according to claim 1, ***characterized in that*** said particle beam is a beam of charged and/or neutral particles where said particle beam preferably comprising mainly electrons and photons.

3. A device for producing a plasma in a heat carrier for stabilization of combustion and neutralization of toxic products, where said device is embodied as an ultra-large-scale-integrated device based on cells of multilayer compositions of different linear and nonlinear dielectrics, metals and semimetals on the metal-ceramic surface of the protective sealed hou-sing arranged in connection with the burning chamber, ***characterized in that***
in said device part of the heat energy of the heat carrier is set to be converted into a particle beam (CPB&NPB) pulse, said particle beam is set to be accelerated, polarized, focused and deflected back to the area of the heat carrier, where in an area of the heat carrier into which said particle beam is set to be directed with said particle beam a highly excited non-equilibrium plasma is set to be generated and heated up for the following initiation of the branching-chain-type plasma-chemical reaction, where in the excited state the plasma retention time is a sum of the single pulse duration of the particle beam and plasma relaxation time up to the beginning of forming of a hot gas to its initial state, where during that time the form of change of the plasma parameters in general follows the pulse shape of the particle beam intensity; and
where part of the heat energy of the heat carrier is set to be continuously converted into a particle beam to generate and heat up plasma so that heat energy conversion process into particle beam becomes self-sustaining oscillatory process with the positive feedback,
where the housing of the device comprising:

at least at least one output window for the particle beam in connection with the burning chamber, at least one heat conducting surface for heat exchange with at least one heat carrier,
a cell for converting heat energy of heat carrier (i.e. hot gases) generated by burning of a mix of fuel and oxidant into high energy particle beam,
a cell for accelerating, polarising and focusing of the particle beam,
a cell for accelerating, polarising, focusing and deflecting of the particle beam for directing beam into predetermined area of volume of the heat carrier,
a cell for filtering and collimation of output particle beam,
a cell for modulating input heat flux, and
a cell of heat inertia to form a pulse of an input heat flux.

4. The device according to claim 3, ***characterized in that*** said window of output particle beam is comprising at least a cell of filtering and collimation of particle beam, said cell comprising in turn at least one set of multi-layered metal films, comprising collimation layer of thick film and/or foil containing micro-holes.

5. The device according to claim 3, ***characterized in that*** said heat conducting surface comprising at least a cell of thermal inertia which in turn comprises at least one set of multi-layered metal-ceramic structure.

6. The device according to claim 5, ***characterized in that*** said cell is in thermal contact with at least one cell for modulating input heat flux, where said cell in turn comprising multi-layered metal-ceramic structure comprising a set of ferroelectrics with electrocaloric effect and ferroelectric-pyroelectric thin films on a substrate of a pyroelectric.

7. The device according to claim 3, ***characterized in that*** said device comprises at least a cell for converting heat energy into the particle beam, where said cell having a vertically-pillar or planar or mixed internal structure

8. The device according to claim 7, ***characterized in that*** said cell comprises at least one cell of heat flux modulation.

9. The device according to claim 7, ***characterized in that*** said cell includes at least one multilayer stack of pyroelectrics, emission targets, pre-accelerator and polarizer of particles, multilayer reflectors, conductors and dielectrics.

10. The device according to claim 9, ***characterized in that*** said device includes at least one pyroelectric stack comprising array of single or different materials having different phase transition temperatures for broadening range of operating temperatures and having different surface shapes and with different surface coating materials.

11. The device according to claim 9, ***characterized by that*** said pre-accelerator and polarizer of particles comprises at least one array of stacks of pyroelectric materials and having different surface shapes and with different surface coating materials.

12. The device according to claim 9, ***characterized by that*** said multi-layered reflectors are in the form of surface coatings and/or dielectric substrates of structural elements.

13. The device according to claim 3, ***characterized by that*** said device comprises at one cell for accelerating, polarising and focusing of the particle beam in a tangential electrostatic field said cell consisting of array of pyroelectric stacks.

14. The device according to claim 3, ***characterized by that*** said device comprises at one cell for accelerating, polarising, focusing and deflecting of the particle beam in tangential electrostatic and magnetic fields, said cell consisting of composite array of pyroelectric stacks and magnetoelectric/multiferroic materials.

15. The device according to claim 3, ***characterized by that*** said device has scalable single design for different of output radiant power and operating temperatures.

Figure 1

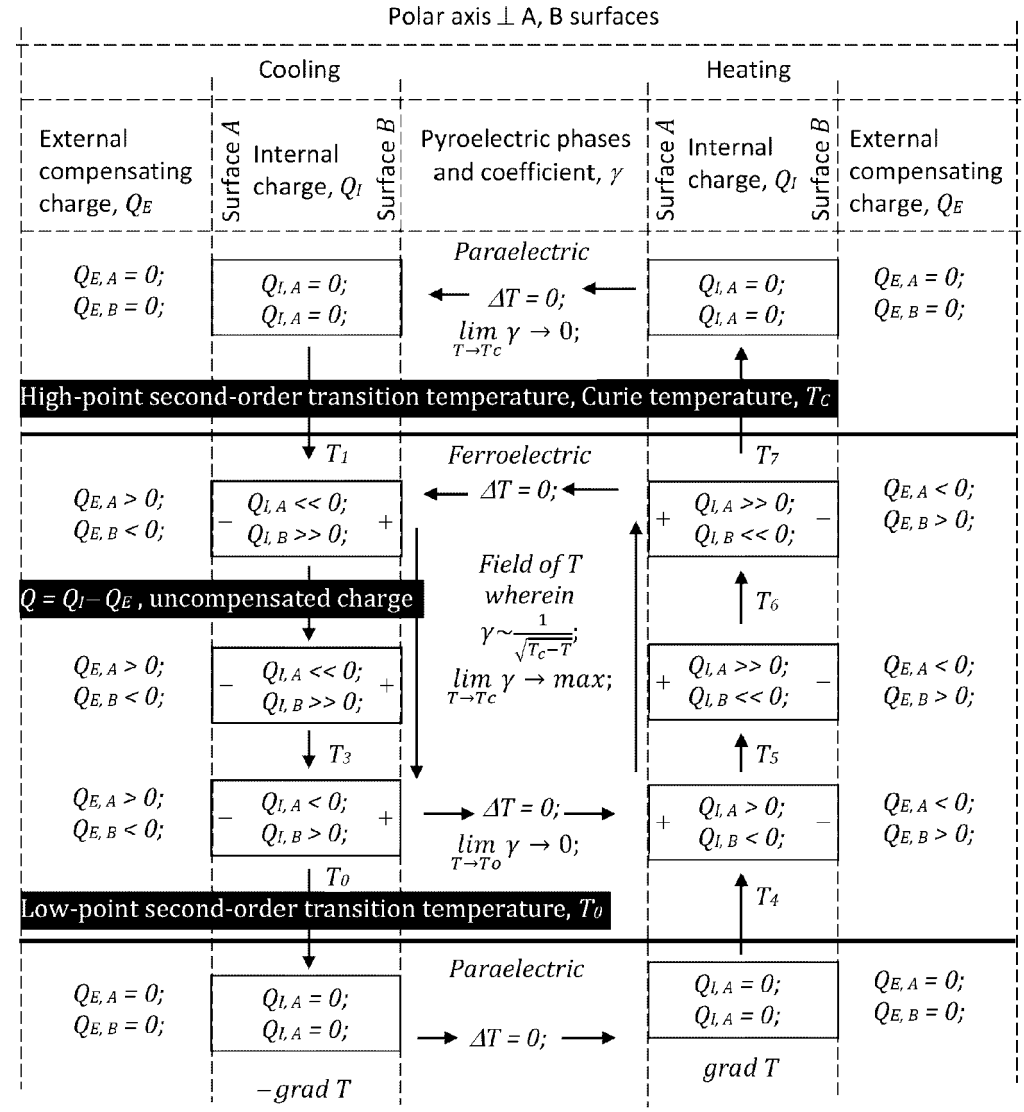
Summary of disclosed embodiments

Disclosed types

- The basic concept of the use of pyroelectric properties.
- Constructive embodiment of the basic concept.
    - Key architectural solutions for pyroelectric stacks.
    - Key solutions on the composition of materials.
    - Key architectural and material solutions for support units.
    - Key architectural solutions for thermoelectronic devices.
- Method for mounting thermoelectronic devices.
- Possible applications of the basic concept.

Figure 2

Schematic of spontaneous polarization (Ps) process of polar dielectrics due to temperature gradient.



a) linear ferroelectric

b) nonlinear ferroelectric

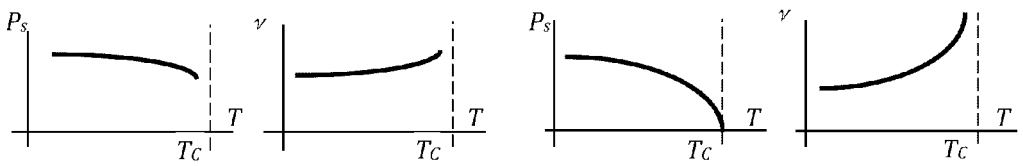
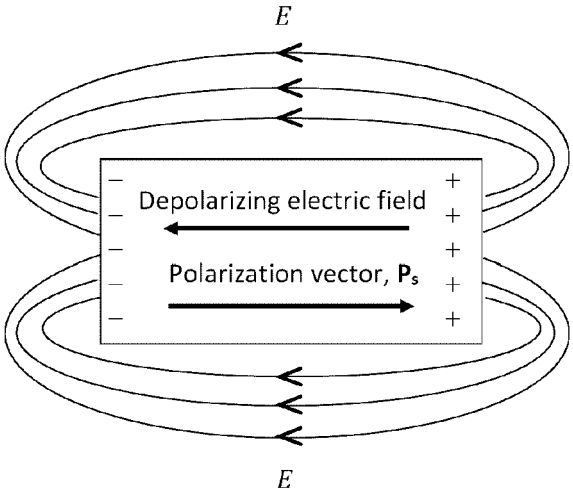


Figure 3

Schematic of dynamical pyroelectric response to temperature changes.

a) Schematic drawing of the electric-lines-of-force of a pyroelectric solid slug.



b) Electrical charge and potential.

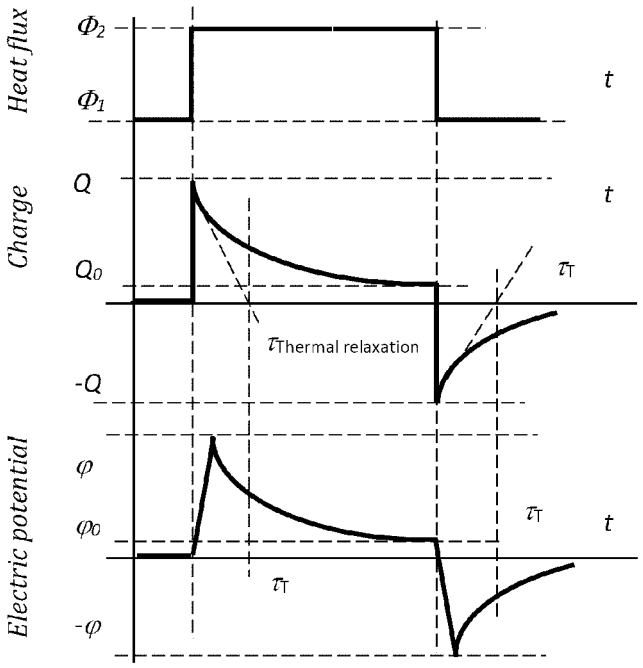
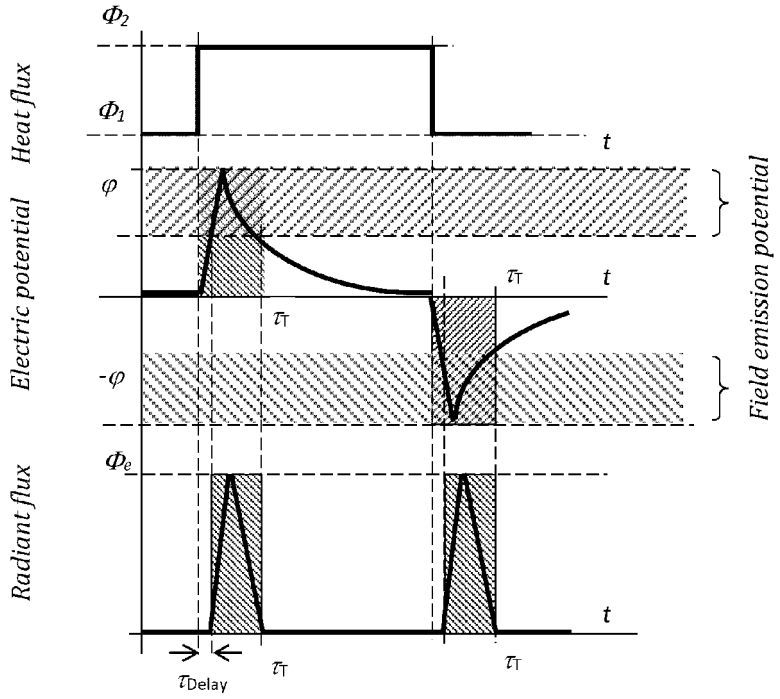


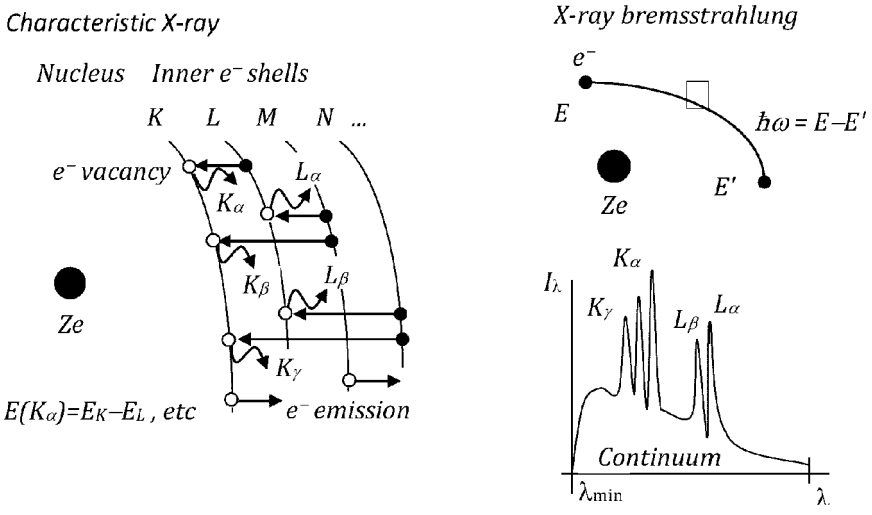
Figure 4

Schematic of dynamical pyroelectric (+ an adjoining medium or target) response, giving off pulsewise radiant flux to temperature changes.

a) Dynamical response of a pyroelectric.



b) X-ray radiation



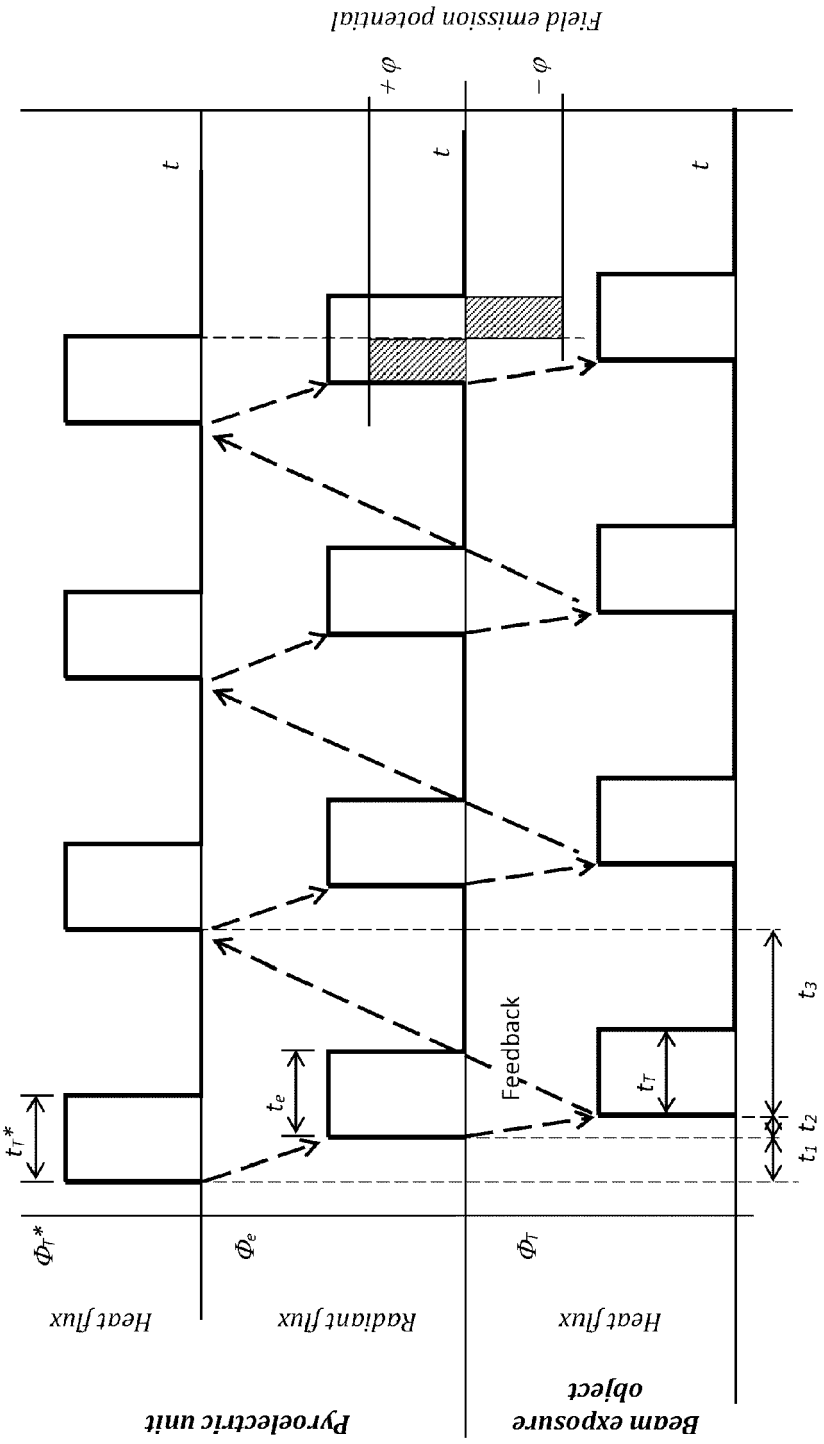


Figure 5

Schematic of thermal positive feedback between a pyroelectric and its generated plasma through energy-exchange

Figure 6

Flowchart of one among many architectural solution of ULSIC device, depending on application.

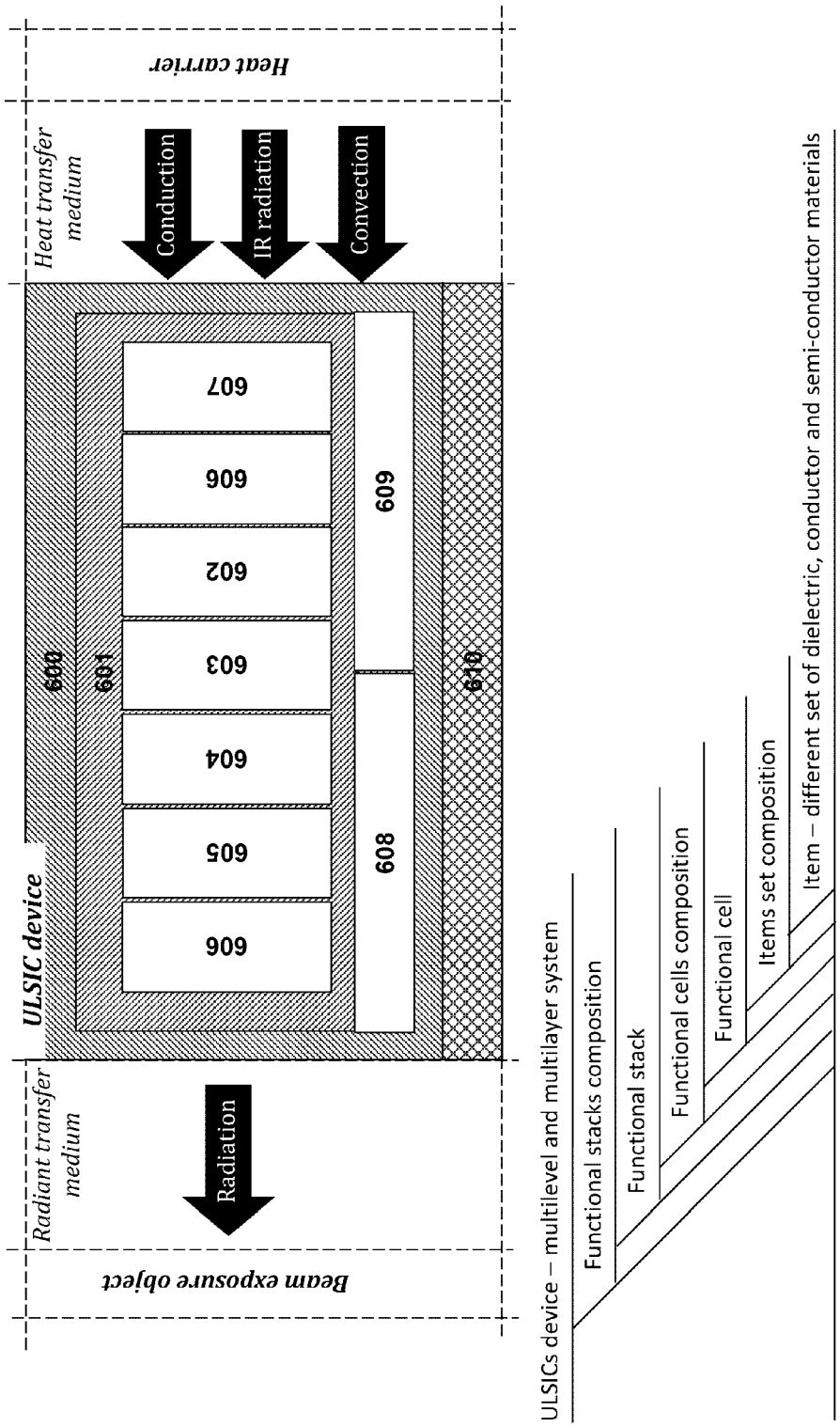
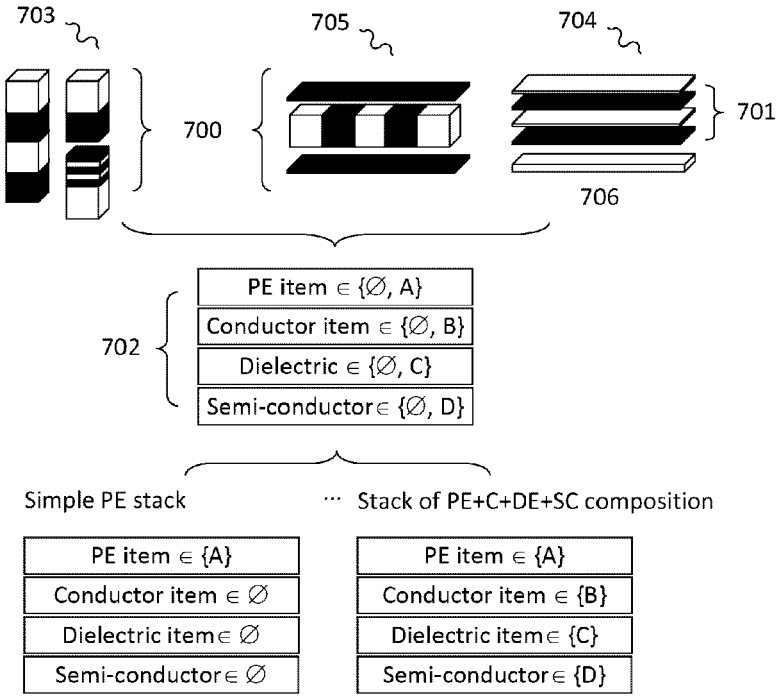


Figure 7

Schematic of components and spatial relationships between parts (items) into PE stack.

a) Basic items of PE stack and spatial relationships



b) Schematic of composition options of different PE items into PE stack

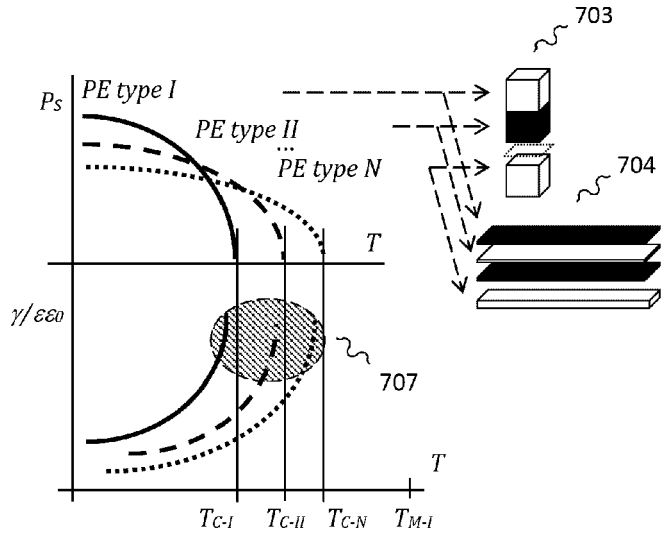
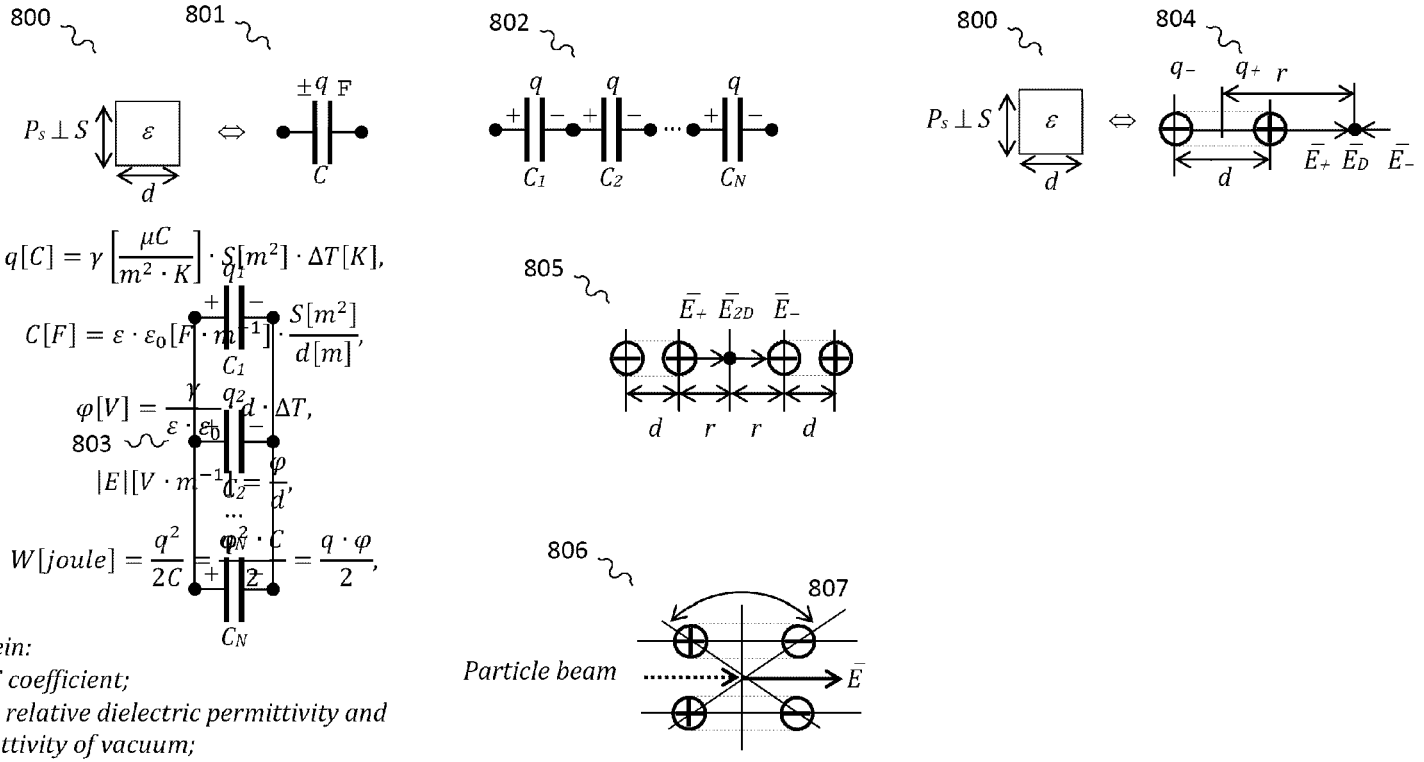


Figure 8

Schematic of quasi-equivalent transformations of a bulk and/or film pyroelectric (PE) item into planar capacitor and dipole model.



$$q[C] = \gamma\left[\frac{\mu C}{m^2 \cdot K}\right] \cdot S[m^2] \cdot \Delta T[K],$$

$$C[F] = \varepsilon \cdot \varepsilon_0[F \cdot m^{-1}] \cdot \frac{S[m^2]}{d[m]},$$

$$\varphi[V] = \frac{\gamma}{\varepsilon \cdot \varepsilon_0} d \cdot \Delta T,$$

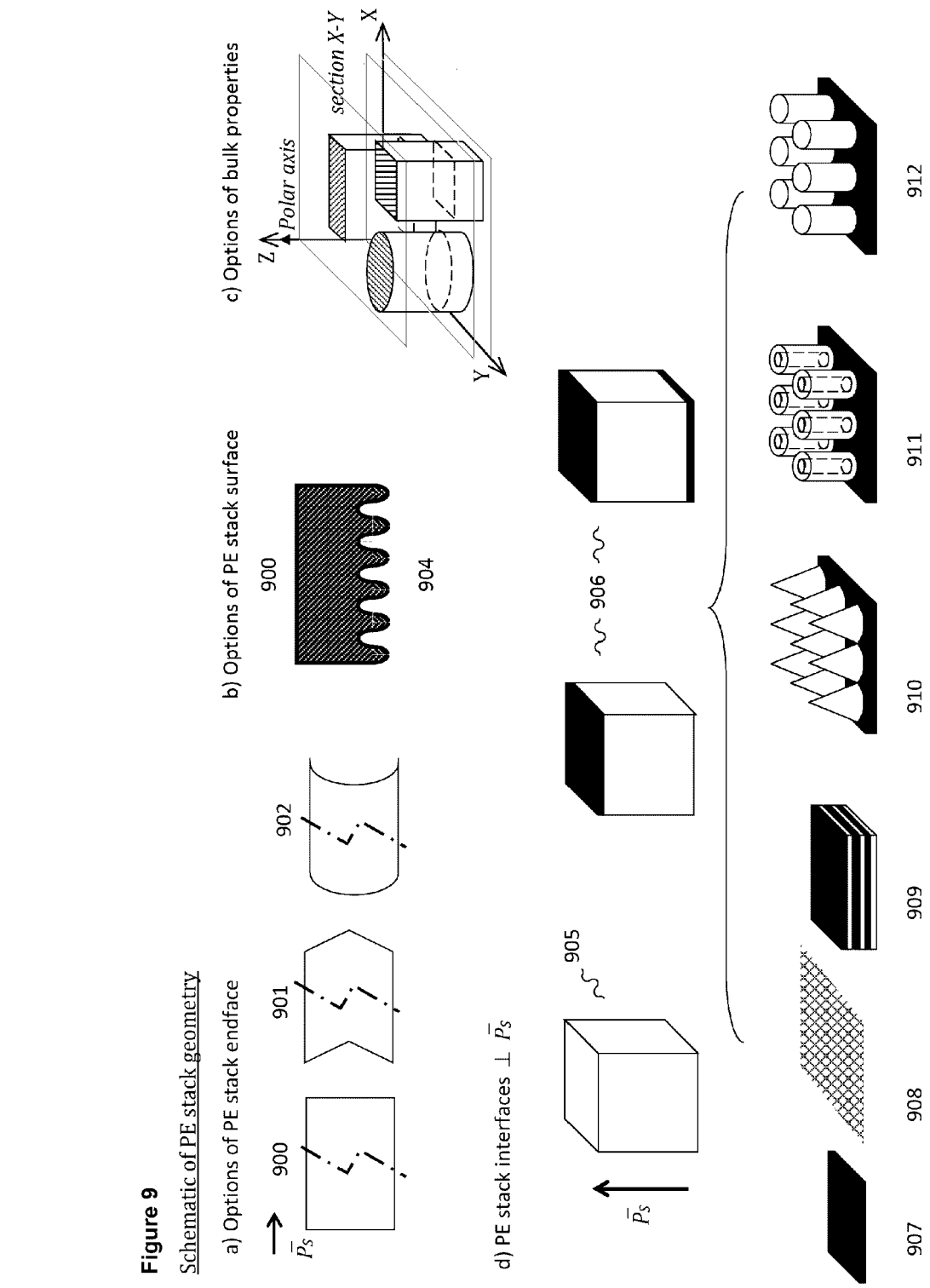
$$|E|[V \cdot m^{-1}] = \frac{\varphi}{d},$$

$$W[joule] = \frac{q^2}{2C} = \frac{\varphi^2 \cdot C}{2} = \frac{q \cdot \varphi}{2},$$

wherein:
γ – PE coefficient;
ε, ε_0 – relative dielectric permittivity and permittivity of vacuum;
S – surface area of the charge; and
d – thickness

Figure 9

Schematic of PE stack geometry



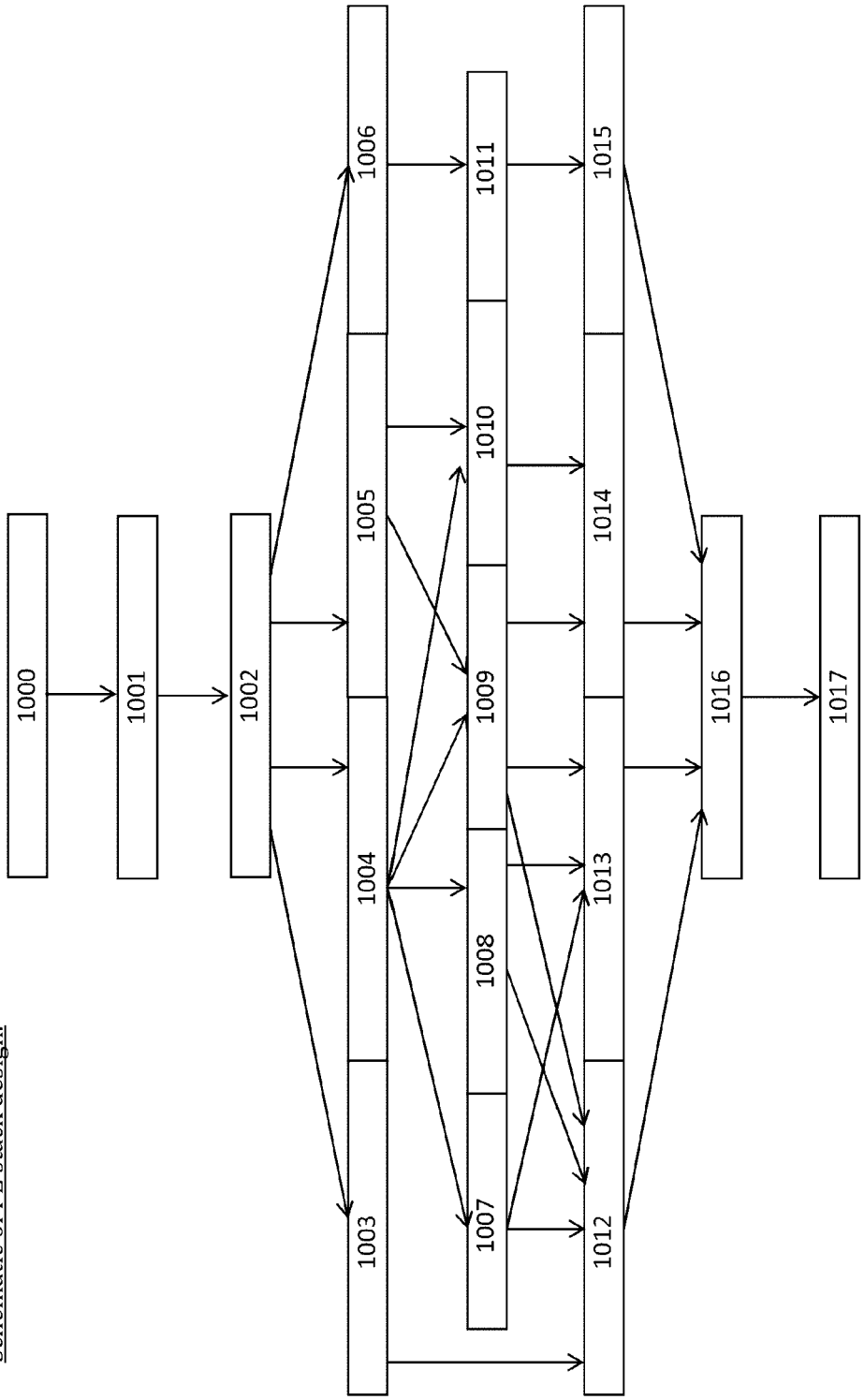


Figure 10

Schematic of PE stack design.

Figure 11

Schematic of manipulation useful properties of different ferroelectric by using electrostatic field.

a) Magneto-electric effect for magnetic fields-base manipulation. b) Electro-caloric effect for thermal fields-base manipulation

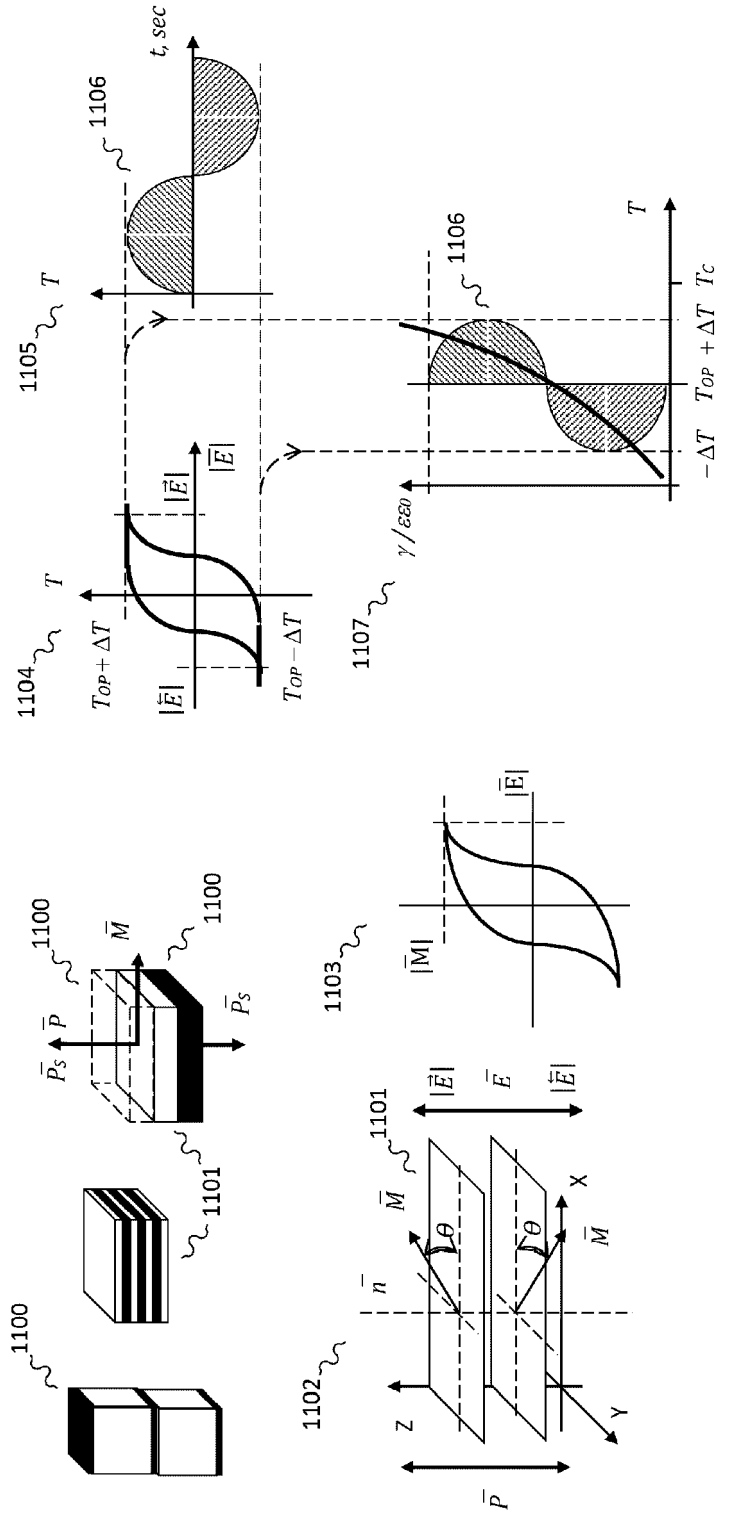


Figure 12

Schematic of spatial relationships between reflectors and other parts of CPB&NPB cell

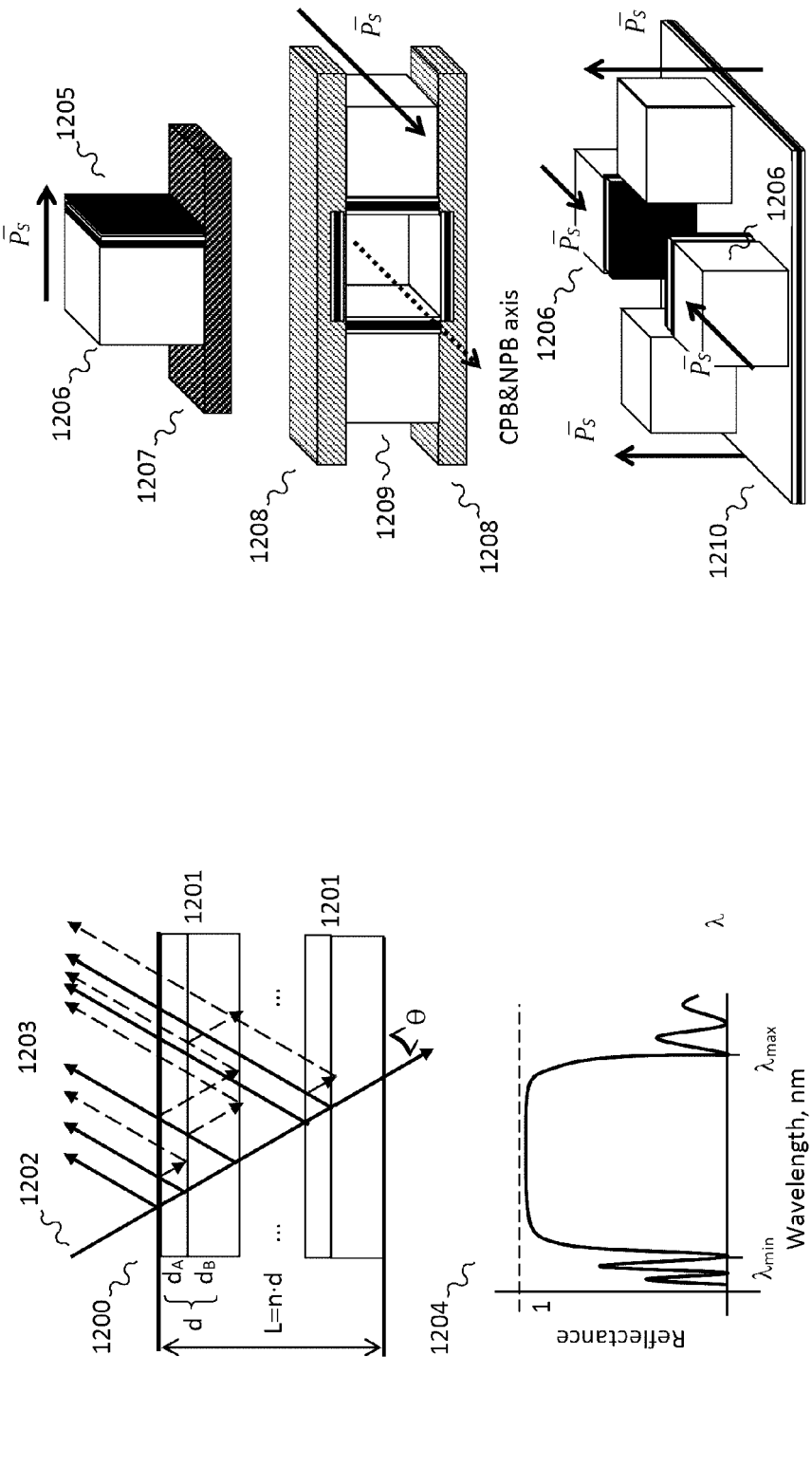
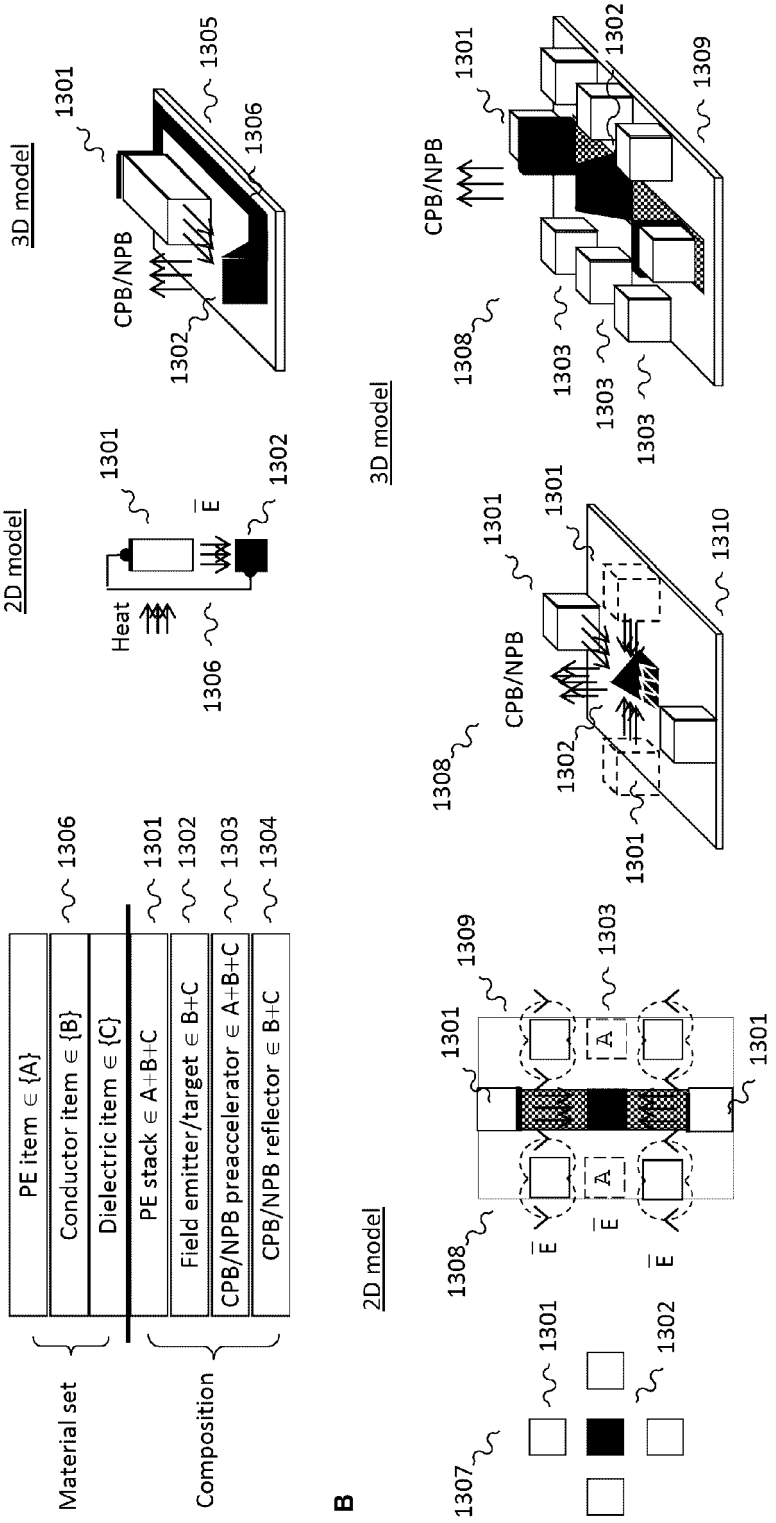


Figure 13

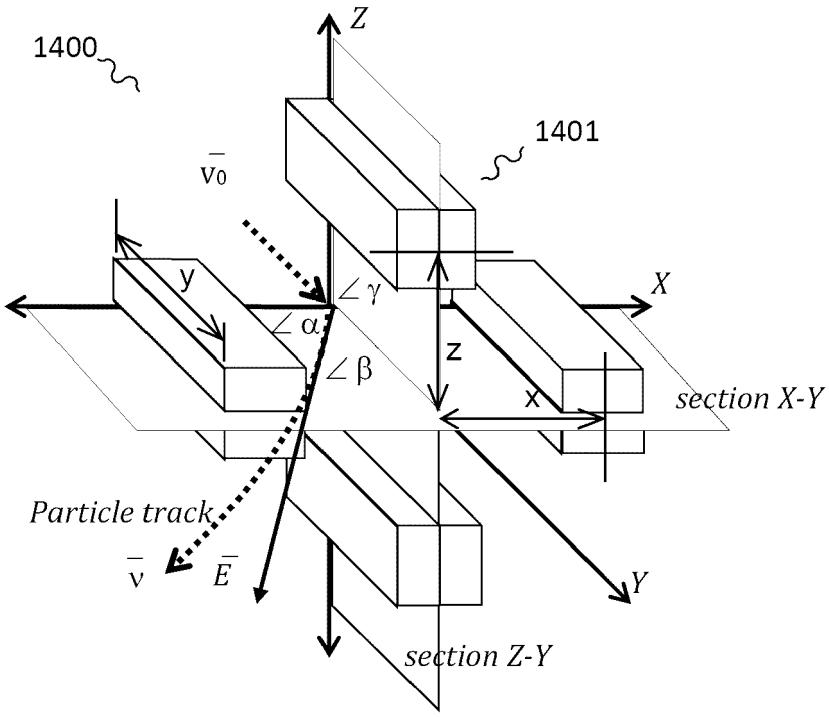
Schematic of components and spatial relationships between parts of CPB&NPB cell. Option A and B



Material set	Composition
PE item ∈ {A}	
Conductor item ∈ {B}	
Dielectric item ∈ {C}	
	PE stack ∈ A+B+C
	Field emitter/target ∈ B+C
	CPB/NPB preaccelerator ∈ A+B+C
	CPB/NPB reflector ∈ B+C

Figure 14

Schematic of one among many options a bulk, spatial configurations and component parts of xyz deflecting cell.



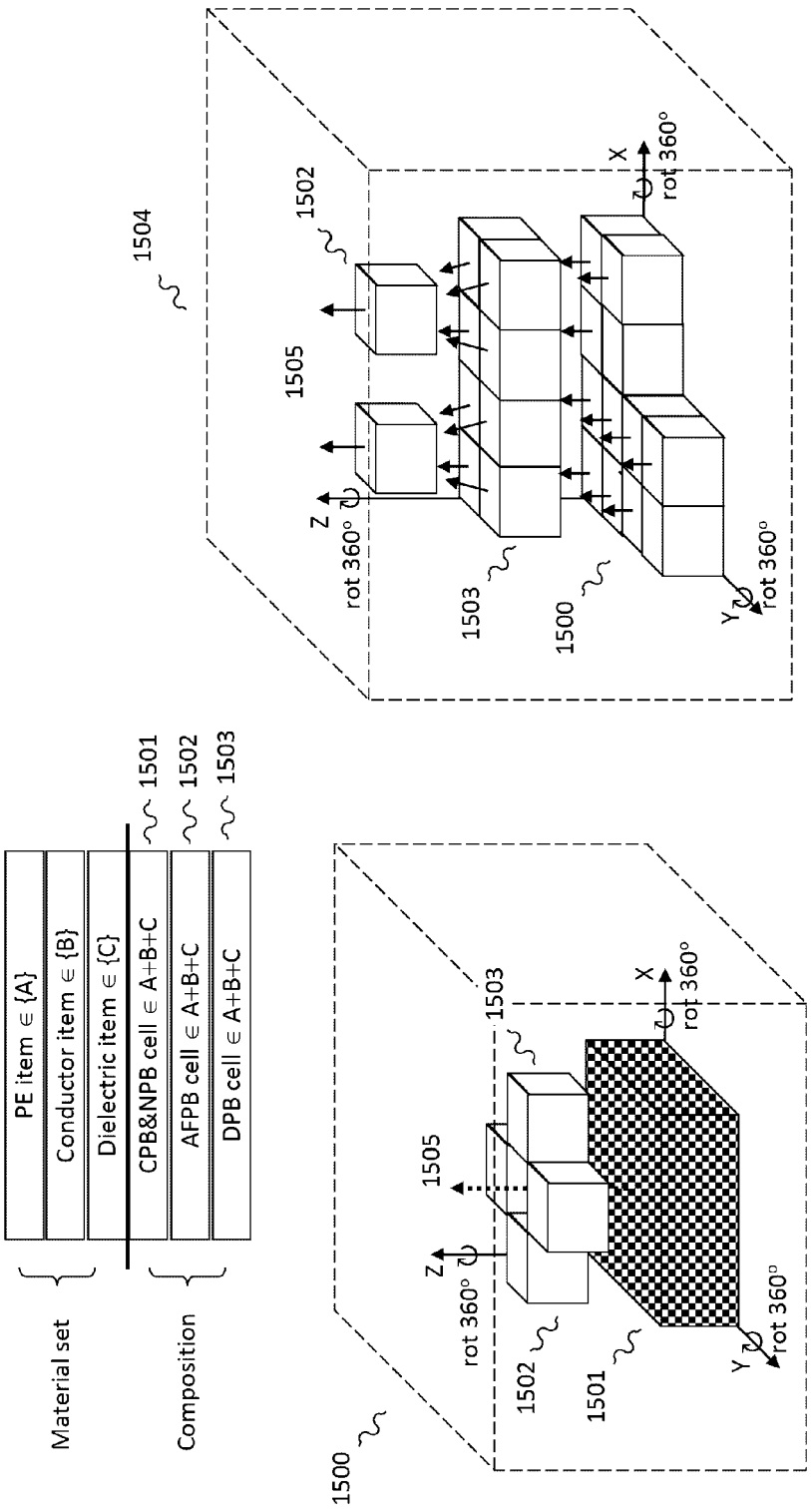


Figure 15

Schematic of design options of CPB & NPB stack.

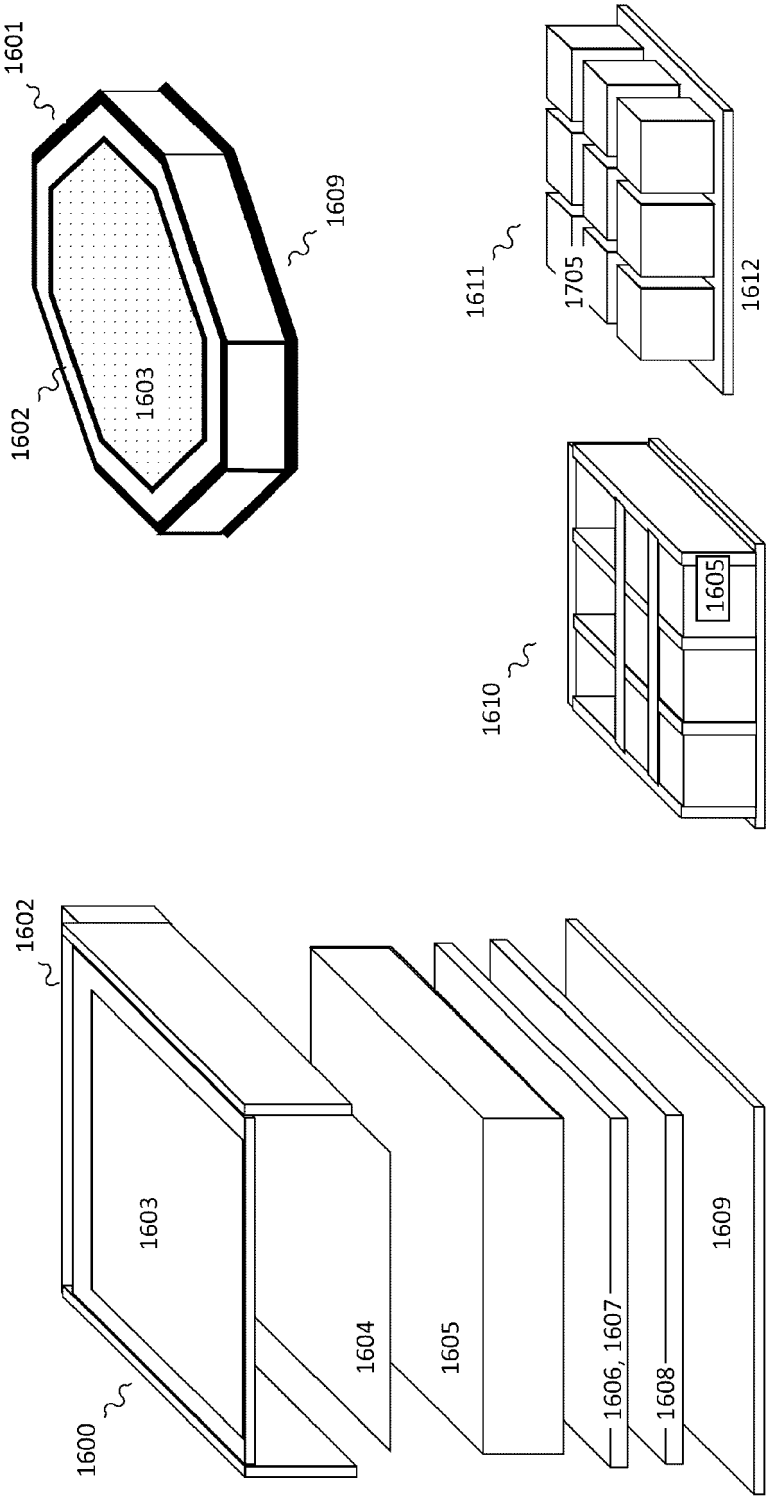


Figure 16

Schematic of model chip housings and built-in-place CPB & NPB stacks.

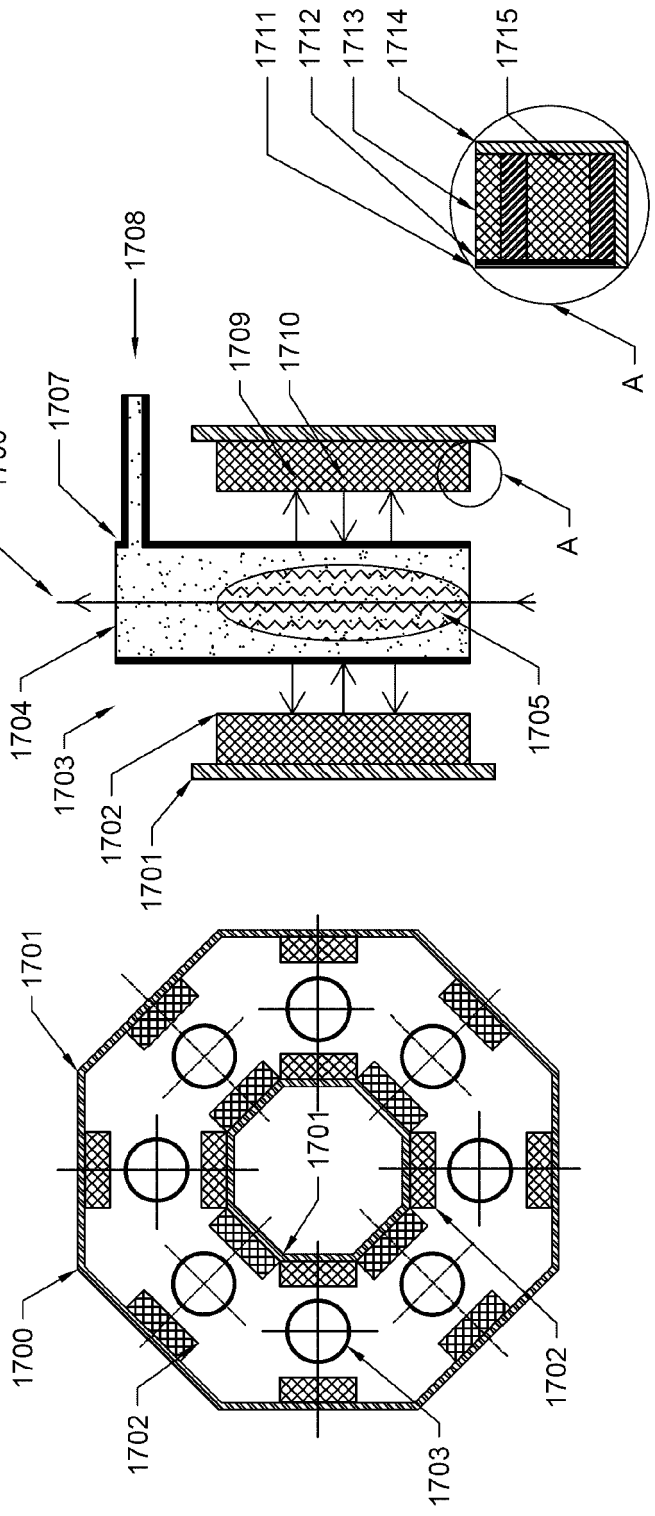


Figure 17

Example of embodiment of ULSIC-device in a hydrogen power cell for micro-CHP apparatus .

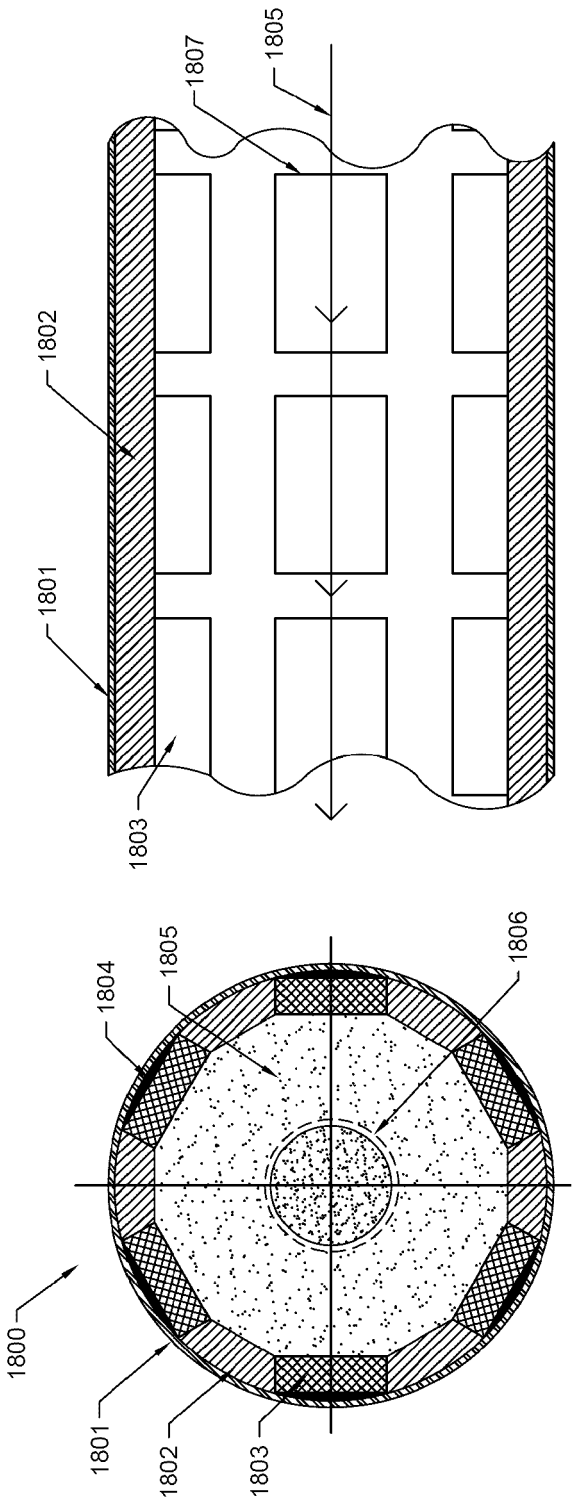


Figure 18

Example of embodiment of ULSIC-device in a toxic neutralization apparatus.

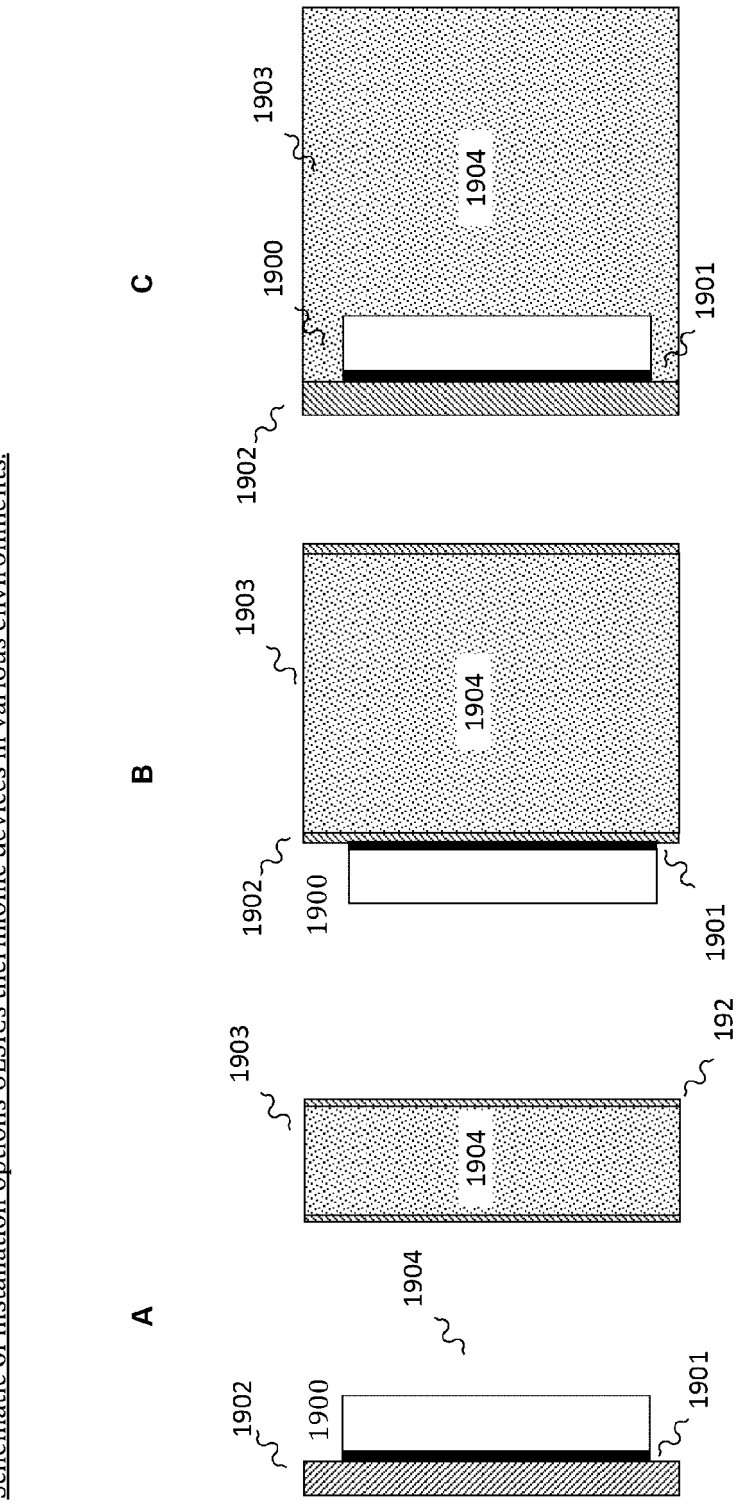
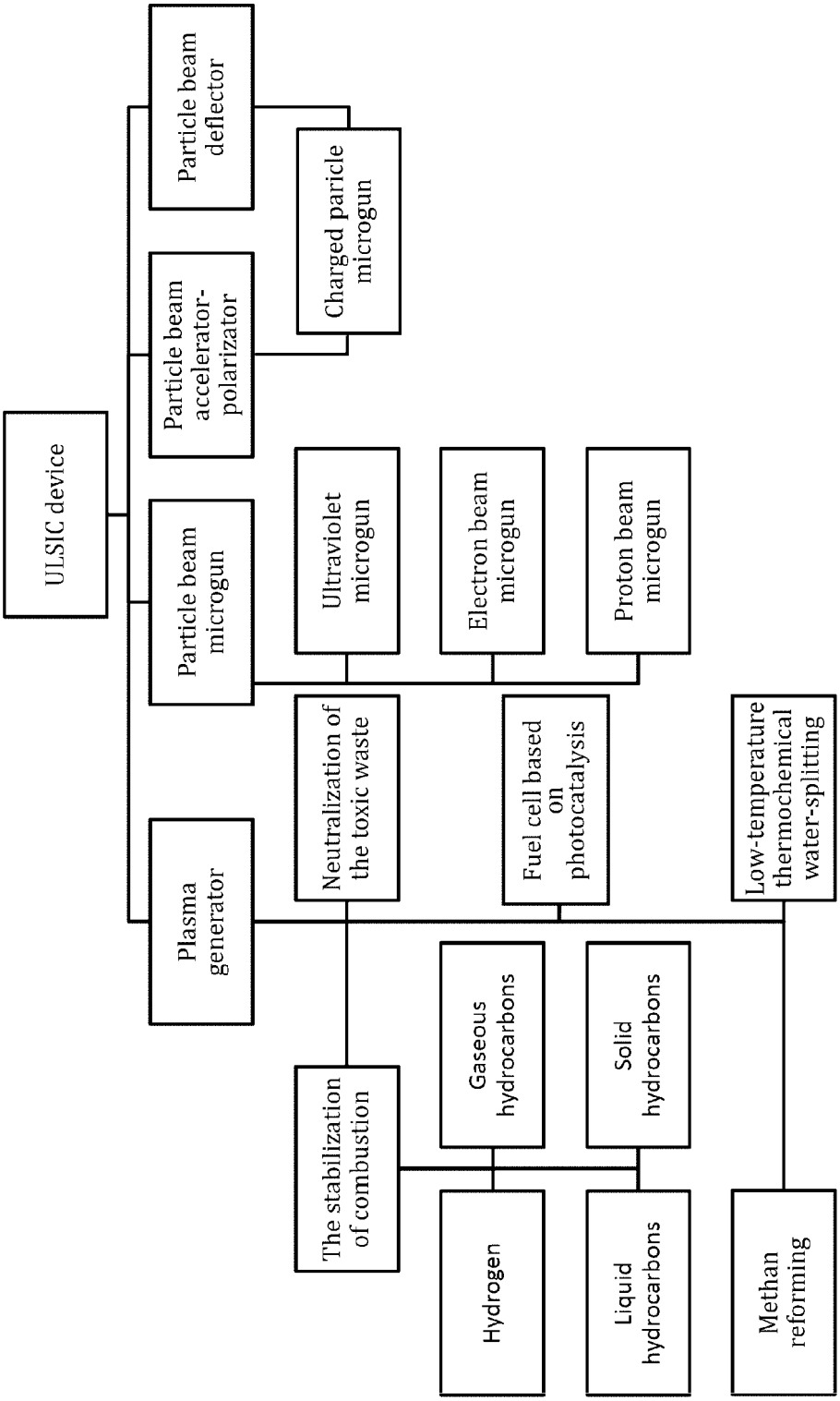


Figure 19

Schematic of installation options ULSICs thermionic devices in various environments.

Figure 20

Schematic of design options of ULSIC devices, and relevant applications.



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EUROPEAN SEARCH REPORT

Application Number
EP 16 18 2997

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
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TECHNICAL FIELDS SEARCHED (IPC)

H05H

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
The Hague	17 February 2017	de Ruijter-Noordman

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17-02-2017

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