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(54) **PLASMA SOURCE DEVICE AND PLASMA ACCELERATOR APPARATUS FOR LASER-DRIVEN ACCELERATION OF ELECTRONS AND CREATION OF X-RAYS**

(57) A plasma source device 100 for providing a gas volume 1 in a plasma accelerator apparatus 200 comprises a capillary channel device 10 for guiding a gas flow 2, with an irradiation port 10A for receiving laser light 3 along an irradiation direction deviating from an axial flow direction of the gas flow 2 and with an output port 10B aligned with the irradiation port 10A and arranged for an output of a plasma accelerator output 4, including electron and/or X-ray beams, wherein the gas volume 1 is provided by gas of the gas flow 2 traversing an irradiation path 5 between the irradiation port 10A and the output port 10B. The capillary channel device 10 comprises multiple capillary channels 11, 12, wherein each of the capillary channels 11, 12 has two radial pinholes 13, the capillary channels 11, 12 are arranged side by side with all pinholes 13 being aligned in series so that the irradiation path 5 through the capillary channel device 10 along the irradiation direction z is provided, wherein a first pinhole 13 of a first capillary channel 11 is the irradiation port 10A and a last pinhole 13 of a last capillary channel 12 is the output port 10B, and the gas volume 1 comprises multiple gas sections 14, 15 arranged along the irradiation path 5, wherein each of the gas sections 14, 15 is provided with predetermined gas parameters by one of the capillary channels 11, 12. Furthermore, a plasma accelerator apparatus 200 and a method of creating electron and/or X-ray beams are described.

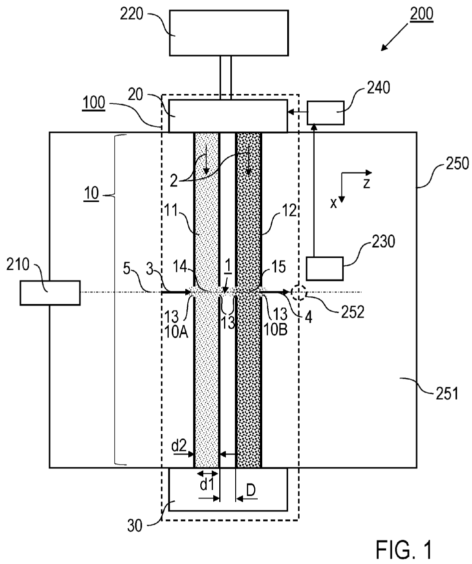

FIG. 1

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Description

Field of the invention

[0001] The invention relates to a plasma source device, being configured for providing a localized gas volume (localized plasma source) in a plasma accelerator apparatus (laser driven wakefield accelerator) for laser-driven acceleration of electrons and/or creation of X-rays. Furthermore, the invention relates to a plasma accelerator apparatus including the plasma source device. Furthermore, the invention relates to a method of creating a plasma accelerator output, including electron and/or X-ray beams, in particular to a method of accelerating electrons, wherein the plasma source device and the plasma accelerator apparatus are used. Applications of the invention are available in the creation of electron beams and optionally X-ray and γ-ray beams, e.g. for medical applications, material investigations or scientific research.

Technical background

[0002] In the present specification, reference is made to the following prior art illustrating technical background of the invention and related techniques:

[1] K. Schmid and I. Veisz, "Supersonic gas jets for laser-plasma experiments", Rev. Sci. Instrum. 83, 053304 (2012);

[2] C. Thaury et al., "Shock assisted ionization injection in laser-plasma accelerators", Nat. Sci. Rep., 5, 16310 (2015);

[3] T. L. Audet et al., "Gas cell density characterization for laser wakefield acceleration", Nuc. Inst. & Meth. A, 909, 383 (2018);

[4] D. J. Spence & S. M. Hooker, "Investigation of a hydrogen plasma waveguide", Phys. Rev. E, 63, 015401 (2000);

[5] M. Kirchen et al., "Optimal Beam Loading in a Laser-Plasma Accelerator", Phys. Rev. Lett., 126, 174801 (2021);

[6] M. J. Garland et al., "Plasma Sources and Diagnostics", Proc. Of the 2019 CERN-Accelerator School on High Gradient Wakefield Accelerators (2019);

[7] B. Farace et al., "Confined Continuous-Flow Plasma Source For High-Average-Power Laser Plasma Acceleration", arXiv:2205.02763v1 [physics.acc-ph] 5 May 2022; and

[8] W. P. Leemans et al., "Multi-GeV electron beams from capillary-discharge-guided sub-peta-watt laser pulses in the self-trapping regime", Phys. Rev. Lett. 113, 245002 (2014).

[0003] Laser-driven plasma accelerators represent a powerful tool for accelerating particles, which have been developed as an alternative to conventional radio-frequency-cavity-based accelerators. In a laser-driven plasma accelerator, a high intensity laser (peak intensity of order 10^{18} W/cm^2 or higher) interacts with a plasma (with electron density of order 10^{17} to 10^{20} cm^{-3}). The laser pulse propagates through the plasma and excites a trailing electron density wave (plasma wave) which gives rise to longitudinal electric fields of up to hundreds of GV/m which can be used to accelerate electrons to high energy. The plasma accelerator generally comprises a pulsed laser source creating laser pulses and a plasma source coupled with a source of gas ([1] to [8]). The plasma source is a region within the plasma accelerator which contains the plasma, or initially a neutral gas, which is converted to plasma when subjected to a high intensity laser pulse or electrical discharge. By the effect of the laser pulses, the plasma wave is created which accelerates the electrons included in the plasma to energies in MeV to multi GeV-range [8] and optionally creates an additional beam of X-rays.

[0004] Various types of plasma sources are known as summarized in the following. Firstly, in a gas jet source, neutral gas is ejected via a jet nozzle into a vacuum chamber in the vicinity of a focus of the laser pulses where the gas is ionized to a plasma (see e.g. [1], [2]). Small obstructions, e.g. from a razor blade or wire, create shocks within the flow of the neutral gas to create a bump in the longitudinal density profile which can aid in electron injection into the accelerating structure. The application of the gas jet source is limited in practice as the gas jet source creates a very high gas load on the surrounding accelerator. Furthermore, the gas jet tends to be unstable, so that it is difficult to control the plasma in a precise and reproducible manner. Finally, it can be difficult to localize a gas profile, create a density ramp (density gradient) or control a longitudinal profile of a gas jet.

[0005] In a gas cell source as another type of plasma source, the neutral gas is confined within a box or cell, with small pinholes at either end, aligned to the optical axis of the pulsed laser to allow the laser pulses to enter and exit the source (see e.g. [3]). The length of the source can be adjusted in-situ to change the length of the interaction region. The gas cell source has an improved stability and allows an easy diagnostic as well as an adjustment of the plasma via changing the cell length.

[0006] However, there are disadvantages due to difficulties in tailoring a longitudinal density profile beyond length change or creating long density ramps. Furthermore, the gas cell also creates a high gas load on surrounding accelerator.

[0007] Furthermore, capillary-based sources are known, wherein the plasma is created in a capillary (see e.g. [4], [5], [8]). The capillary has its primary longitudinal flow axis aligned to the laser irradiation axis, such that the laser light travels along the capillary axis. Neutral gas enters the capillary via attached feeder tubes and propagates out to the vacuum chamber along the laser axis. The capillary may be operated with neutral gas, or with preformed plasma (by means of an electrical discharge). The feeder tubes may contain different gases, which mix in the bulk capillary to create a longitudinal density profile suitable for electron injection. Addition of an electrical discharge can create a radial plasma density profile suitable for guiding the laser light over long distances. The capillary-based source allows a stable operation, can create basic longitudinal density profiles, and can be coupled with a discharge to allow for laser guiding. However, limitations result from a medium gas load on a surrounding accelerator, the impossibility of fine tuning of the whole longitudinal density profile and the creation of long density ramps.

[0008] According to the modified capillary-based source proposed in [7], the laser irradiation axis is perpendicular to the longitudinal flow axis of the capillary. The capillary has two aligned radial pinholes providing an irradiation port for receiving laser pulses and an output port for outcoupling the laser and radiation generated by the laser-driven plasma accelerator (e.g. electrons and X-rays). The laser intersects the capillary transversely, drives a plasma wave and accelerates electrons out of the output port. This plasma source provides a continuous and spatially confined gas volume and minimises the gas load in the acceleration chamber.

[0009] However, the gas source of [7] has limited options for adjusting the plasma density profile and/or plasma parameters in the capillary. As further disadvantages, it has been found that the energy spectrum of the electrons accelerated with the gas source of [7] is relatively broad, while the obtainable spectral amplitude of the beam of accelerated electrons is relatively low, and parameters of the beam of accelerated electrons have a limited reproducibility. All these limitations may restrict the use of the source of [7] for practical applications.

[0010] Generally, the following main challenges are associated with conventional plasma sources:

1.) Localisation: Creating a highly localised region of gas in vacuum (i.e. creating a source where a ramp in pressure from full gas pressure to vacuum is short) remains a difficult problem and has a large impact on the generated electron or X-ray beams.

2.) Containment: Removing the "spent gas" after the interaction is important to reduce the load on the chamber vacuum pumps of the plasma accelerator. Current designs simply expel the gas into the vacuum chamber. Even at low accelerator repetition rates, this puts a large stress on the vacuum pumps. At high accelerator repetition rates, this gas load necessitates use of auxiliary differential pumping systems to maintain high vacuum in the rest of the plasma accelerator.

3.) Tailoring: Conventional techniques have restricted capabilities in tailoring the longitudinal profile of the gas pressure only and controlling in detail the dynamics of the laser plasma acceleration.

4.) Tuneability: Dynamic, high-fidelity, in-situ tuning of the longitudinal profile of gas pressure is difficult to achieve in practice although has significant benefits for controlling of the plasma accelerator.

Objective of the invention

[0011] It is an objective of the invention to provide an improved plasma source device, plasma accelerator apparatus and/or method for creating a plasma accelerator output, in particular for accelerating electrons and/or creating X-rays, being capable of avoiding disadvantages of conventional techniques. In particular, the inventive technique is to be capable of improving gas localization even with increased gas quantities, improving gas containment, adjusting and/or tuning a gas flow and/or plasma parameters for creating the plasma wave, modifying and/or adding density gradients within the gas flow, narrowing the energy spectrum of the electrons accelerated within the plasma source, improving the reproducibility of parameters of the beam of accelerated electrons and/or X-rays and/or increasing the electron beam's repetition rate, in particular while the gas load into the plasma accelerator is kept low compared with gas jet sources and the stability of plasma generation is kept high.

Summary of the invention

[0012] This objective is solved by a plasma source device, a plasma accelerator apparatus and/or a method of creating a plasma accelerator output, comprising the features of the independent claims. Advantageous embodiments and applications of the invention are defined in the dependent claims.

[0013] According to a first general aspect of the invention, the above objective is solved by a plasma source device, being configured for providing a localized gas volume in a plasma accelerator apparatus, comprising a capillary channel device being arranged for guiding and confining a gas flow, wherein the capillary channel device comprises an irradiation port being arranged for receiving laser light along an irradiation direction deviating from an axial flow direction of the gas flow in the capillary channel device and an output port being aligned with the irradiation port along the irradiation direction and being arranged for an output of a plasma accelerator output, including electron and/or X-ray beams, from the plasma source device, wherein the gas volume is provided by gas of the gas flow traversing a continuous irradiation path between the irradiation port and the output port.

[0014] According to the invention, the capillary channel device comprises multiple capillary channels, wherein each capillary channel has two radial pinholes. The capillary channels are arranged side by side with all pinholes being aligned in series so that the irradiation path through the capillary channel device along the irradiation direction is provided. A first pinhole of a first capillary channel within the capillary channel device is the irradiation port and a last pinhole of a last capillary channel within the capillary channel device is the output port. The capillary channels are configured for providing gas sections with predetermined gas parameters along the irradiation path.

[0015] The plasma source device generally provides an enclosed space within the plasma accelerator apparatus which contains the gas volume and plasma and which opens towards an application site of the plasma accelerator apparatus. The plasma source device is adapted for an operation in the plasma accelerator apparatus, i.e. the plasma source device is a component which is coupled with the plasma accelerator apparatus. Depending on the application thereof, the plasma source device may be a fixedly connected or removable component. The plasma source device delivers the gas with the capillary channel device, i.e. it is a capillary-based device, similar to the technique of [7]. Deviating from [7], the capillary channel device includes multiple capillary channels, i.e. two or more capillary channels.

[0016] Each capillary channel is a hollow conduit with a first end for gas supply and a second end for gas collection. Preferably, the capillary channels, in particular the first ends thereof, are separated from each other, so that different gases can be supplied to each of the capillaries, and/or the second ends are separated from each other, so that gases can be collected from each of the capillaries to another collection reservoir. Alternatively, two or more of the first and/or second ends may be connected, e.g. merged, so that a common gas may be supplied to two or more of the capillary channels.

[0017] One or more of the capillary channels may include an internal structure at an inner surface of the capillary channel, preferably just upstream from the pinholes, wherein the internal structure is configured for applying an abrupt change to the gas flow within the capillary channel. The internal structure preferably may comprise a notch-, step- or tip-shaped mechanical barrier protruding into the capillary channel perpendicular to the flow direction of the gas in the capillary channel. For example, the internal structure may comprise a notch or step or tip being positioned and shaped for inducing a shock in the gas flow. Advantageously, the internal structure supports the modification and/or generation of gas density gradients in the localized gas volume of the plasma source device.

[0018] According to a further modification of the invention, at least one, preferably all of the capillary channels may be provided with a plasma excitation device, being arranged in the capillary channel, e.g. upstream from the pinholes thereof, particularly preferred directly adjacent to the pinholes of the capillary channel. The plasma excitation device may comprise e.g. an electrode connected with a power source. By applying an electrical voltage, e.g. relative to another electrode or ground, plasma can be excited within the gas flowing in the capillary channel, in particular in the gas section through which the laser propagates.

[0019] Due to the provision of multiple capillary channels, the gas flow in the capillary channel device is provided by multiple gas sub-flows (partial flows) and the axial flow direction of the gas flow in the capillary channel device is represented by the axial flow directions of each of the gas sub-flows in the capillary channels. Preferably, the capillary channels have a straight shape. The straight shape may have advantages for providing well defined flow conditions. With the straight shape, the axial flow direction in a capillary channel is the axial (longitudinal) direction of the capillary channel.

[0020] Alternatively, at least one of the capillary channels may have a curved shape, which may have advantages for an adaptation of the capillary channel device to the available space within the plasma accelerator apparatus. With the curved shape, the axial flow direction in a capillary channel is the local axial (longitudinal) direction of the capillary channel at the two radial pinholes thereof. At least one of the capillary channels may comprise a tube-shaped conduit, in particular a self-supporting conduit, or alternatively at least one of the capillary channels may be integrated in a carrier body.

[0021] Each capillary channel has two radial pinholes. The pinholes of one capillary channel are located aligned to each other at opposite channel walls. Preferably, the pinholes are coaxially aligned with the laser light along the irradiation direction, i.e. with the laser propagation axis. The pinhole facing to the irradiation port may be called upstream pinhole, and the opposite pinhole facing to the output port may be called downstream pinhole. The capillary channels are arranged as a row such that the pair of pinholes of each capillary channel is aligned with all pairs of pinholes of the remaining capillary channels. By the pinholes, a straight irradiation path through the capillary channel device is created. The irradiation path extends along the irradiation direction. A pinhole of a first capillary channel of the row of capillary channels arranged side by side is exposed for incoupling laser light (first pinhole), so that it provides the irradiation port of the capillary channel device. On the opposite side of the capillary channel device, a pinhole of a last capillary channel of the row of capillary channels is exposed for outcoupling laser light and the plasma accelerator output, so that it provides the output port of the capillary channel device.

[0022] Pinhole diameters are preferably below 1 mm, in particular below 500 μm, and at least 10 μm, in particular at least 20 μm. The inner cross-sectional dimension, in particular inner diameter, of the capillary channels, in particular along the irradiation direction, is preferably below 5 mm, in particular below 1 mm, and at least 10 μm, in particular at least 20 μm. The pinhole diameters determine a shape (steepness) of the density ramp of the gas volume along the irradiation direction. With increasing the pinhole diameter, the density ramp is flattened, and with reducing the pinhole diameter, the density ramp is steepened.

[0023] According to the invention, the localized gas volume to be created comprises multiple gas sections arranged along the irradiation path, wherein each of the gas sections is provided with predetermined gas parameters by one of the capillary channels. The localized gas volume is a localised region of gas in an evacuated space, in particular in a vacuum chamber of a plasma accelerator apparatus. The gas volume is mainly localised by the enclosing capillary channels and resulting from the small dimension of the pinholes. Due to the gas sub-flows in the capillary channels, the irradiation path crosses multiple gas sub-flows, each providing a gas section. Within the capillary channel device, the irradiation path extends along a series of gas sections. Each gas section extends at least over the cross-sectional dimension of one of the capillary channels between the pinholes thereof. Generally, the gas section extends from the upstream pinhole of a capillary channel to the upstream pinhole of the neighbouring capillary channel. By adjusting the gas in each of the capillary channels, the gas sections are provided with the predetermined gas parameters.

[0024] In each gas section, in particular in at least one gas section at an upstream side of the capillary channel device, i.e. towards the irradiation port thereof, a neutral gas or a plasma (ionized gas) is provided to produce a beam of accelerated electrons (and possibly an additional beam of X-rays).

[0025] The number of capillary channels providing the capillary channel device can be selected in dependency on the particular application conditions of the plasma source device. Preferably, the capillary channel device may comprise 2 to 5 capillary channels. The invention is not restricted to this number of channels. More than 5 capillary channels can be provided as well. Employing only two capillary channels has advantages in terms of the simplified structure of the capillary channel device and the gas supply. Providing more than two capillary channels has advantages resulting from an improved tunability of the gas profile along the irradiation path and can be advantageous for certain applications.

[0026] According to a second general aspect of the invention, the above objective is solved by a plasma accelerator apparatus being configured for creating a plasma accelerator output, including electron and/or X-ray beams, comprising a laser source device being arranged for creating pulsed laser light, a gas source device being arranged for providing at least one gas species, and the plasma source device according to the first general aspect of the invention or an embodiment thereof. The plasma source device is coupled with the gas source device, and the laser source device is arranged for irradiating the gas volume provided by the gas sections in the irradiation path. The laser source device preferably is configured for creating laser pulses with a repetition frequency in a range from 1 Hz to 100 kHz. The plasma accelerator apparatus has an evacuated space into which the plasma accelerator output is to be emitted from the plasma source device. Preferably, the plasma source device is arranged in the evacuated space. Advantageously, the plasma accelerator apparatus is a multi-kHz laser driven wakefield accelerator, in particular being capable of producing electrons with a mean energy of 5 MeV or more.

[0027] According to a third general aspect of the invention, the above objective is solved by a method of creating a plasma accelerator output, including electron and/or X-ray beams, wherein the plasma source device according to the first general aspect of the invention or an embodiment thereof and the plasma accelerator apparatus according to the second general aspect of the invention or an embodiment thereof is used, comprising the steps of providing a gas volume of at least one gas species with the plasma source device, said gas volume including the multiple gas sections along the irradiation path of the plasma source device, irradiating the gas sections along the irradiation path with laser light and creating a plasma wave in the gas sections, including injecting electrons into the plasma wave formed in the gas sections and accelerating the electrons, and output of the plasma accelerator output to be obtained.

[0028] Advantageously, the inventive plasma source device provides additional degrees of freedom in adjusting a gas volume and/or plasma parameters for creating the plasma wave in the gas sections. A specific gas species with a specific gas density (or: pressure) and/or flow velocity may be supplied specifically to each of the multiple capillary channels, so that a gas profile may be formed along the irradiation path within the capillary channel device. Compared with the technique of [7], the gas profile can be extended without increasing the gas load to the evacuated space of the plasma accelerator apparatus. Additionally, features of each gas section can be adjusted by selecting capillary channels with specific cross-sectional dimensions, e.g. diameters, and/or specific diameters of the pinholes and/or specific spacings between neighbouring capillary channels. Accordingly, density gradients within the gas profile along the irradiation path can be added.

[0029] As a further important advantage, the inventors have found, that the energy spectrum of the electrons accelerated with the inventive plasma accelerator apparatus can be narrowed, while the spectral amplitude and/or peak charge of the beam of accelerated electrons simultaneously is increased.

[0030] Advantageously, the above main challenges associated with conventional plasma sources regarding localisation, containment, tailoring and/or tunability are addressed by the invention as follows. With regard to the localisation of the gas and plasma for plasma acceleration, the inventors have found that controlling gas density ramps (plasma density transition from the plasma source device output port to vacuum) may have a substantial impact on the accelerated electron beams. For controlling the length scale of these ramps, the inventive plasma source device provides multiple capillary channels, which allow to control the length of the ramp of each individual capillary channel individually, in particular by selecting the diameter of its pinhole. Preferably, this can be done symmetrically or asymmetrically to change the ramp on each side. Further, the flow geometry in the capillary channels can increase the velocity of the gas perpendicular to the irradiation direction (laser axis) near the pinhole, further localising the gas to the capillary structure.

[0031] For improving the containment, the gas is confined within a continuous flow capillary structure, with a sub-flow in each capillary channel, e.g. perpendicular to the laser axis, so that much of the gas never leaves the plasma source device and never reaches the plasma accelerator vacuum. The lower gas load reduces the need for an auxiliary differential pumping system.

[0032] The inventive plasma source device also allows tailoring the gas volume and plasma creation by creating a longitudinal density profile of the plasma source via the multiple capillary channels for the first time. In particular, the stacking of multiple capillary channels one after the other, optionally with different densities and/or gas species and/or gas species mixtures, allows for the creation of the tailored longitudinal plasma density profile. In addition, the internal structure of each capillary may be tailored to control the flow e.g. by addition of a notch to induce a shock in the flow. The inventors have found substantial advantages in particular for electron beam injection, energy gain, and beam emittance. With the capillary channels, a longitudinal structure may be added to the neutral gas profile - and so in turn to the plasma density profile - along the irradiation direction, thus offering to unlock the full potential of laser driven plasma accelerators.

[0033] With regard to the tunability, the invention provides particular advantages as laser plasma accelerators are machines which rely on highly nonlinear physics. This means that relatively small changes, such as systematic experimental uncertainties, in the input parameters can constitute a relatively large shift in the systems outputs, i.e. the electron or optionally X-ray beam parameters. This means the plasma source device preferably is operated with in-situ and operando tuning, wherein the operational parameters, including those related to the plasma source device, should be able to be varied in-situ and operando, to fully optimize the accelerator. This capability is obtained by the provision of the multiple capillary channels, because each capillary channel may be supplied by a variable gas supply, in particular gas supply system, preferably including a gas species/-mixture selector and mass flow controller. The multiple separate capillary channels allow for in-situ and operando varying of each capillary's gas species and the mass flow/pressure inlet conditions. Extended over multiple capillary channels, this allows for high fidelity in-situ and operando tailoring of the longitudinal density profile including changing the total integrated plasma areal density, i.e. plasma length multiplied by plasma density, of the plasma source and fundamentally changing the form of the longitudinal density profile.

[0034] In summary, the multiple, individually controllable capillary channels provide a new continuous flow geometry to improve gas containment and localization. With the use of multiple capillary channels in series, each capillary channel is capable of acting to independently control a small slice of longitudinal gas profile. This allows high-fidelity control of the longitudinal density profile. The capillary channels provide separate gas inlets and exhausts for each capillary channel to allow for independent in-situ and operando tuning of the entire plasma source device.

[0035] Further advantages of the invention result from the ability of the inventive plasma accelerator apparatus to create a beam of accelerated electrons with a high average current and high energy, e.g. in a range from 5 MeV to 100 MeV, in particular with pulsed kHz electron acceleration with a compact design, and to provide a continuous and spatially confined gas flow, while minimising the gas load in the acceleration chamber.

[0036] According to a preferred embodiment of the invention, the capillary channels may be arranged for providing the gas sections with the gas parameters including at least one of gas species, gas densities and gas density gradients along the irradiation path. Preferably, at least two gas sections have different gas parameters. Advantageously, the inventors have found that with the gas parameters gas species, gas density and gas density gradient, the plasma accelerator outputs can be optimized.

[0037] According to another preferred embodiment of the invention, the plasma source device further may comprise a gas supply control device being capable of coupling the capillary channel device with a gas source device. The gas supply control device is configured for adjusting the gas parameters of the gas sections along the irradiation path. The gas supply control device comprises a plurality of supply lines, each of which being connected with one of the capillary channels and including a flow control element, like a tunable and/or switchable valve, wherein the supply lines are connectable with one or more gas reservoirs of the gas source device of the inventive plasma accelerator apparatus. Alternatively, the gas source device may be considered as a part of the gas supply control device, i.e. as a part of the inventive plasma source device. Optionally, the gas supply control device may include mixer elements configured for setting a mixture of two or more gas species to be supplied to one or more of the capillary channels.

[0038] Advantageously, the gas supply control device improves the tunability of the plasma source device. Particularly preferred, at least one of a gas species, a gas composition and a gas pressure in at least one of the capillary channels and/or an overall areal density of the gas sections along the irradiation path can be set with the gas supply control device.

[0039] With a further advantageous embodiment of the invention, the gas supply control device may be configured for an in-situ and operando control of the gas parameters of the gas sections and/or an overall areal density of the gas sections along the irradiation path, in particular during operation of the plasma accelerator apparatus. For example, the overall areal density (gas density) of the gas sections along the irradiation path can be tuned by tuning a gas pressure within the capillary channels. Accordingly, the plasma source device can be tuned during the operation thereof. For tuning the plasma source device, preferably a control device is included in the plasma source device and/or the plasma accelerator apparatus.

[0040] Particularly preferred, the plasma accelerator apparatus may comprise a sensor device being arranged for detecting at least one parameter of the plasma accelerator outputs leaving the output port, and a control loop device being arranged for tuning the plasma source device in dependency on a sensor signal of the sensor device. In terms of the method, creating the plasma accelerator outputs preferably may comprise detecting at least one parameter of the plasma accelerator outputs leaving the output port and tuning the plasma source device in dependency on the detected at least one plasma accelerator output parameter. The output parameter of the plasma accelerator leaving the output port comprises e.g. the electron beam spectrum, its energy spread, the beam charge, the beam divergence and others, or X-ray beam spectrum, divergence, photon flux and others, which can be sensed with sensors like electron spectrometers, charge detectors, charge-coupled-detectors, scintillators and others. The control loop device provides particular advantages for an automatic stabilization of the plasma wave generation and electron acceleration.

[0041] According to further preferred embodiments of the invention, the pinholes (pinhole diameters) and/or inner diameters of at least one of the capillary channels may have different dimensions compared with the pinholes and/or inner diameters of at least one neighbouring capillary channel. Advantageously, a gas density gradient along the irradiation path can be preset by selecting the pinhole diameters and/or inner capillary channel diameters. The plasma source device may be designed for creating a preset gas density gradient, i.e. the plasma source device may be adapted as a hardware component being configured for a particular acceleration task. Preferably, a pinhole diameter of an upstream pinhole of a capillary channel may be smaller than the pinhole diameter of a downstream pinhole of said capillary channel.

[0042] As a further preferred feature of the invention, the pinholes of at least one of the capillary channels may have different diameters so that the gas section within at least one of the capillary channels has a gas density gradient along the irradiation path between the pinholes. The gas density gradient is tunable by setting the pinhole diameters. The direction (sign) of the gas density gradient can be set by providing an upstream capillary with lower gas density than a downstream capillary and/or pinhole larger than the downstream pinhole (increasing gas density along irradiation direction) or an upstream capillary with higher gas density than a downstream capillary and/or pinhole smaller than the downstream pinhole (decreasing gas density along irradiation direction).

[0043] According to a particularly preferred embodiment of the invention, the capillary channels may be configured for providing the gas sections such that the gas parameters in a first gas section (gas section at an upstream side of the capillary channel device) are selected for creating an injection of electrons into the plasma wave in response to the irradiation of the gas with the laser light and that the gas parameters in a subsequent second gas section (gas section at a downstream side of the capillary channel device) are selected for accelerating the electrons in response to the irradiation of the gas with the laser light.

[0044] Advantageously, the inventors have found that the provision of multiple capillary channels allows tailoring the gas profile along the irradiation path for improving the laser plasma acceleration. The capillary channels provide independently and precisely tunable gas sections. In particular, the gas profile can be adjusted such that injection of the free electrons into the plasma wave and the acceleration of the electrons can be decoupled from each other. At least one of the upstream gas sections can be adjusted for setting injection conditions and at least one of the downstream gas sections can be adjusted for setting different acceleration conditions in the gas profile, e.g. by providing different gas species, densities and/or density ramps. As a result, the beam quality of the accelerated electrons can be improved in terms of e.g. stability, reproducibility and range. Injection conditions are typically achieved by high gas density (up to few 10^{20} cm^{-3}), or very short density downramps, or selection of gas species with tightly bound inner-shell electrons. In particular, optimal injection conditions are characterised by a strongly localised injection region (e.g. a high density or injection gas species region extending only for tens of μm or a density downramp as short as 10 μm). Acceleration conditions are usually achieved by longer propagation lengths (up to 1 mm, depending on the laser source used in the interaction) and at lower gas densities.

[0045] Advantageously, plural variants are available, which may be provided alone or in combination for designing the inventive plasma source device, wherein, according to the invention, the laser light irradiation direction is inclined relative to the axial flow direction(s) of the gas sub-flows in the capillary channel device. According to a first variant, the capillary channels and the pinholes are arranged with an alignment such that the irradiation path is perpendicular to a capillary gas flow direction of each capillary channel. With the perpendicular orientation, advantages for providing well-defined flow conditions along the irradiation path are obtained.

[0046] According to a further variant, at least two of the capillary channels may be arranged with capillary gas flow directions inclined relative to each other. In particular in combination with the first variant and straight capillary channels, the inclination means that the capillary channels are turned relative to each other in a plane perpendicular to the irradiation direction. Advantageously, this facilitates a coupling of the ends of the capillary channels with gas supply and gas collection components. According to yet a further variant, at least two of the capillary channels, preferably all capillary channels, may be arranged with parallel capillary gas flow directions. At least two of the capillary channels, preferably all capillary channels, are parallel, at least at the location of the irradiation path. This embodiment of the invention has advantages in terms of compactness of the plasma source device.

[0047] With further preferred modifications of the inventive plasma source device, the arrangement of the capillary channels relative to each other may be varied as follows. Preferably, at least two of the capillary channels, particularly preferred all capillary channels, may contact each other along the irradiation path. Advantageously, the gas sections are enclosed by the capillary channels in radial directions relative to the irradiation direction, so that a load of the surrounding evacuated space with gas is avoided. Alternatively or additionally, at least two of the capillary channels, particularly preferred all capillary channels, may be spaced from each other along the irradiation path. A free gap may be provided between the downstream pinhole of at least one of the capillary channels and the upstream pinhole of the next neighbouring one of the capillary channels. Advantageously, the spacing allows the fine tuning of the length of the gas density gradients. Alternatively or additionally, at least two of the capillary channels, particularly preferred all capillary channels, are provided as channels in a solid block, in particular being made of sapphire, thus improving the mechanical stability of the plasma source device in an advantageous manner. Preferably, the solid block may comprise a monolithic carrier substrate.

[0048] According to a further advantageous embodiment of the invention, at least one, preferably all, of the capillary channels may have an inner flattened shape along the irradiation path. The flattened shape means that the inner shape of the at least one capillary channel is an oval shape deviating from a circular shape, so that a cross-sectional dimension of the capillary channel in a direction perpendicular to the irradiation direction is bigger than a cross-sectional dimension of the capillary channel in a direction along the irradiation direction. Advantageously, with the flattened shape, the laser has a shorter path in the gas/plasma and moreover the pinholes size (which will be on the bigger side of the oval inner shape) may be varied in an increased range. Accordingly, the flattened shape allows a short length gas channel with less restrictions on the upstream and downstream pinholes size.

[0049] Additionally or alternatively, at least one, preferably all, of the capillary channels may have an inner elongated shape along the irradiation path. Again, the elongated shape means that the inner shape of the at least one capillary channel is an oval shape deviating from a circular shape, but with a cross-sectional dimension of the capillary channel in a direction perpendicular to the irradiation direction being smaller than a cross-sectional dimension of the capillary channel in a direction along the irradiation direction. Advantageously, with the elongated shape, increasing the length of the gas section is possible without increasing the gas consumption.

Brief description of the drawings

[0050] Further advantages and details of the invention are described in the following with reference to the attached drawings, which schematically show in:

Figure 1:	features of embodiments of the plasma source device and the plasma accelerator apparatus according to the invention;
Figures 2 and 3:	features of preferred variants of the capillary channel;
Figure 4:	variants of features of capillary channels within the plasma source device;
Figure 5:	details of a gas supply control device of an embodiment of the plasma source device according to the invention; and
Figure 6:	an illustration of advantageous features of accelerated electrons obtained with the inventive technique.

[0051] Detailed description of preferred embodiments of the invention

[0052] Embodiments of the inventive plasma source device and plasma accelerator apparatus and the operation thereof are described in the following with particular reference to the design of the plasma source device. Details of the plasma accelerator apparatus and the method of accelerating electrons are not described as far as they are known from conventional techniques. In particular, the selection of gas species, the adjustment of laser parameters, the initial creation of plasma, the provision of at least one plasma excitation device, the creation of the plasma wave and/or the design of the vacuum chamber of the plasma accelerator apparatus may be implemented as it is known per se from conventional techniques.

[0053] It is emphasised that the drawings represent schematic illustrations only. Practical embodiments may differ from the illustrations, in particular with regard to the sizes, shapes and arrangement of the capillary channels and/or the design of pinholes within the capillary channels. The invention is not restricted to embodiments with two capillary channels, as shown in the drawings. The plasma source device may be structured with more than two capillary channels, for instance for introducing further degrees of freedom in the design of the gas volume along the irradiation direction.

[0054] Details of operation conditions of the plasma accelerator apparatus can be selected by a user based on tests, reference data, e.g. selected with a single capillary accelerator, and/or numerical simulations, based on [6], in particular in dependency on application conditions of the accelerator. Furthermore, operation conditions can be loop-controlled in dependency on parameters of a measured plasma accelerator output.

[0055] Figure 1 illustrates a cross sectional view of an embodiment of a plasma source device 100 being included in an embodiment of the plasma accelerator apparatus 200. The plasma accelerator apparatus 200 comprises a laser source device 210, a gas source device 220, the plasma source device 100, and optionally a sensor device 230 as well as a control loop device 240. The laser source device 210 is arranged for creating pulsed laser light 3. As an example, the laser source device 210 comprises a laser system delivering high peak power (> 50 GW) and ultrashort pulses (down to few femtoseconds). The gas source device 220 comprises one or more gas reservoirs including at least one gas species to be supplied as a gas flow 2 to the plasma source device 100. Furthermore, the plasma accelerator apparatus 200 comprises a vacuum chamber 250, which accommodates the plasma source device 100 and which provides an evacuated reaction space 251 where a plasma accelerator output, e.g. a beam of accelerated electrons 4 is to be created. At an application site 252, a target substance (not shown) e.g. a material with high atomic number, may be arranged as a source of X-rays created in response to an irradiation of the target substance with the accelerated electrons 4.

[0056] The plasma source device 100 may be fixedly connected with the remaining components of the plasma accelerator apparatus 200. Alternatively, the plasma source device 100 may be configured as a replacement component for adapting the plasma accelerator apparatus 200 for a particular acceleration task. As the replacement component, the plasma source device 100 may comprise coupling parts for a detachable connection with the plasma accelerator apparatus 200, for instance a vacuum chamber thereof.

[0057] The plasma source device 100 comprises the capillary channel device 10 with a first capillary channel 11 and a second capillary channel 12. At least one, preferably all of the capillary channels 11, 12 is designed for instance as free-standing capillary with a support frame 16 (see Figure 2) or as a channel in a monolithic carrier substrate 18 (see Figure 3).

[0058] With the illustrated embodiment, the capillary channels 11, 12 have a straight shape, and they are arranged in parallel with each other. The longitudinal direction of the capillary channels 11, 12 defines a flow direction of the gas flow 2 (provided by two sub-flows) through the capillary channels 11, 12. According to the illustration, the axial flow direction of the gas flow 2 in the capillary channels 11, 12 is considered to be parallel to an x axis.

[0059] Each capillary channel 11, 12 has two radial pinholes 13 (see Figure 4). Each pinhole 13 is a wall opening in a capillary wall. The pinholes 13 are open in radial directions perpendicular to the flow direction x of the capillary channels 11, 12. The radial pinholes 13 of each capillary channel 11, 12 are arranged in an aligned manner in opposite wall sections of the capillary wall.

[0060] In the plasma source device 100, the capillary channels 11, 12 are arranged such that all pinholes 13 are aligned relative to each other. Accordingly, a straight line is opened, which crosses all capillary channels 11, 12 and which provides an irradiation path 5 through the capillary channel device 10. With the illustrated example, the pinholes 13 are arranged such that the irradiation direction defined by the irradiation path 5 runs perpendicular to the flow direction x of the capillary channels 11, 12. The gas of the gas flow 2 traversing the irradiation path 5 provides the gas volume 1 to be created.

[0061] Furthermore, the plasma source device 100 comprises a gas supply control device 20, which is arranged for coupling an upstream end of the capillary channel device 10, in particular first ends of the capillary channels 11, 12 for gas supply with the gas source device 220 of the plasma accelerator apparatus 200. In particular, the gas supply control device 20 is arranged for receiving at least one gas species from the gas source device 220 and for supplying the at least one gas species to the capillary channels 11, 12. With the gas supply control device 20, gas parameters of the gas flow through the capillary channel device 10 are adjusted. With preferred examples, the gas supply control device 20 may be adapted for supplying a particular gas species to each of the capillary channels 11, 12 and to adjust the gas density of the supplied gas species in each of the capillary channels 11, 12, and/or the gas supply control device 20 may be adapted for mixing different gas species for supplying a mixture with a preset mixing ratio to one or more of the capillary channels 11, 12 of the capillary channel device 10. Further details of a practical embodiment of a gas system within the gas supply control device 20 are illustrated in Figure 5.

[0062] The gas supply control device 20 may be adapted for an in situ and in-operando control of the gas parameters of the gas volume 1 within the capillary channel device 20. To this end, the plasma accelerator apparatus 200 is provided with a control device (not shown), which may be arranged for tuning the gas supply control device 20, for instance on the basis of a preset control program. Alternatively, as shown in Figure 1, the sensor device 230 and the control loop device 240 may be provided as further components of the plasma accelerator apparatus 200. The sensor device 230 comprises e.g. an electron spectrometer and/or a charge measurement device, and it is arranged for detecting at least one plasma accelerator output parameter, e.g. the electron beam 4 leaving the capillary channel device 10, for instance for detecting electron beam energy or electron beam charge. Based on the detected plasma output parameter, the sensor device creates a sensor signal, which is used by the control loop device 240 for tuning the plasma source device 100, in particular the gas supply control device 20 thereof.

[0063] At a downstream end of the capillary channel device 10, the second ends of the capillary channels 11, 12 are connected for gas collection with a gas collection device 30. The gas collection device 30 comprises for instance a collection reservoir, including a common reservoir for collecting the gas flow from all capillary channels 11, 12, or separate sub-reservoirs for specifically collecting the gas from each of the capillaries 11, 12. As a further alternative, the gas collection device 30 may comprise an interface connecting the second ends of the capillaries 11, 12 with the gas supply control device 20 and/or with the gas source device 220.

[0064] With a practical embodiment, the capillary channels 11, 12 comprise capillaries made preferably of glass with an inner diameter d1 in a range from 10 μm to 1 mm, a wall thickness of 10 μm and an axial length of 5 cm. The pinholes 13 have a diameter in a range from 5 μm to 100 μm. Preferably, the pinholes 13 can be made by the effect of the pulsed laser light 3 in a preparation step. Advantageously, with the preparation of the pinholes 13 with the pulsed laser light 3, which subsequently is used for accelerating electrons, the alignment of the pinholes is automatically obtained and the diameter of the pinholes 13 is limited to the real irradiation path 5 where the laser light 3 crosses the capillary channels 11, 12.

[0065] The capillary channels 11, 12 may be arranged with a distance D along the irradiation path 5, as shown in Figure 1. The distance D may be selected in a range from 10 μm to 1 mm. Alternatively, the capillary channels 11, 12 may contact each other directly (see Figure 4A) without a spacing therebetween. As an example, the laser source device 210 may create pulsed laser light 3 with a centre wavelength of 800 nm, a pulse duration of 5 fs and a repetition rate of 1 kHz.

[0066] The gases supplied comprise at least one suitable gas for laser plasma acceleration, in particular at least one of helium, nitrogen and hydrogen, argon. The gas density in the capillary channel is preferably in a range from 10^{17} cm^{-3} to 10^{20} cm^{-3}, depending on the gas used and the pulsed laser characteristics.

[0067] With the plasma accelerator apparatus 200 of Figure 1, the electron beam 4 is created as follows. The gas flow 2 is created with the gas supply control device 20. As an example, a first gas sub-flow of 1 mg/s of nitrogen is supplied to the first capillary 11 and a second gas sub-flow of 0.3 mg/s is supplied to the second capillary channel 12. Along the irradiation path 5, a gas volume 1 with gas sections 14, 15 is created. The gas flow 2 is adjusted such that the gas sections 14, 15 provide the gas volume 1 as a continuous gas field along the irradiation path 5. All gas sections 14, 15 are connected in longitudinal direction along the irradiation path 5.

[0068] Each of the gas sections 14, 15 provides specific plasma parameters, which are determined by the gas densities in the capillary channels 11, 12, the diameters of the pinholes 13 and the optional distances D between the capillary channels 11, 12. In particular, a gas density gradient is created downstream of the downstream pinhole 13 of the first capillary channel 11 and downstream of the downstream pinhole 13 of the second capillary channel 12. The shape of the gas density gradient can be adjusted by the gas density within the capillary channels 11, 12 and by the diameters of the pinholes 13.

[0069] Advantageously, with the gas supply control device 20, the pressure and/or flow conditions of each capillary channel 11, 12 can be tailored independently. The gas enters continuously from the gas supply control device 20 and is continuously extracted at the gas collection device 30. At the gas collection device 30, the gas either can be pumped out to vacuum exhaust or recycled back into the capillary inlet.

[0070] The pulsed laser light 3 propagates along the irradiation direction z through the concentric pinholes 13. As the pulsed laser light 3 propagates through the structure, it ionizes the neutral gas in the capillary channels 11, 12 and drives a plasma wave. If injection conditions are fulfilled, electrons are injected into the wave and accelerated, forming the plasma accelerator output, e.g. electron beam 4.

[0071] The first pinhole 13 reached by the pulsed laser light 3 provides an irradiation port 10A of the capillary channel device 10, and the last pinhole at the downstream end of the irradiation path 3 provides an output port 10B of the capillary channel device 10. A plasma accelerator output 4 to be created exits the output port 10B for the further application thereof. Parameters of the plasma accelerator output 4 can be sensed with the sensor device 230. In dependency on the detected plasma output parameter, the gas volume 1 can be adjusted using the control device 240 and the gas supply control device 20.

[0072] The capillary channels 11, 12 may be arranged in a common plane parallel to each other, as shown in Figure 1. With this embodiment, the capillary channels 11, 12 are arranged in the plane including the longitudinal extension of the irradiation path 5 (x-z plane, drawing plane). Modified embodiments of the capillary channel device 10 are illustrated in Figures 2 and 3, wherein the capillary channels 11, 12 are not parallel to each other.

[0073] According to Figure 2, the capillary channels 11, 12 of the capillary channel device 10 are supported by a common support frame 16. Each capillary channel 11, 12 has coupling pieces 17 at the ends thereof. The coupling pieces 17 are provided for gas supply or collection. Preferably, the capillary channels 11, 12 are fixed to the support frame 16 via the coupling pieces 17. The support frame 16 extends for instance in the x-y plane perpendicular to the irradiation direction z. Accordingly, the irradiation path 5 extends perpendicular to the drawing plane in Figure 2.

[0074] According to Figure 3, the capillary channels 11, 12 of the capillary channel device 10 are formed in a monolithic carrier substrate 18, which is made of for instance sapphire. The capillary channels 11, 12 are formed in different planes within the carrier substrate 18. The capillary channel device 10 of Figure 3 can be made for instance by creating the first capillary channel 11 in or near an upper surface of the carrier substrate 18 and creating the second capillary channel in or near an opposite, lower surface of the carrier substrate 18. With a hole drilled perpendicular to the plane of the carrier substrate 18, the irradiation path 5 through the capillary channel device 10 can be formed.

[0075] Figure 4 illustrates variants of the capillary channel design in an exemplary manner. In practical embodiments of the plasma source device, different or equal variants of the capillary channel design may be provided by different capillary channels of the plasma source device. According to Figure 4A, a contiguous arrangement of the capillary channels 11, 12 is shown. With this embodiment, the capillary channels 11, 12 are arranged without a spacing therebetween. The gas volume 1 is created along the irradiation path 5 perpendicular to the capillary channels 11, 12.

[0076] Figure 4B shows an embodiment with a spacing (distance D), as shown in Figure 1. Additionally, Figure 4B shows that the pinholes 13 may have different diameters at the upstream and downstream sides of at least one of the capillary channels 11, 12, and/or that the pinholes 13 of the capillary channels 11, 12 may have different diameters.

[0077] In the first capillary channel 11, Figure 4B shows an example of an internal structure 19, preferably directly upstream of the pinholes 13. The internal structure 19 is a tip-shaped mechanical barrier protruding into the capillary channel perpendicular to the gas sub-flow in the capillary channel and applying a schematically illustrated shock 19A to the gas sub-flow for supporting electron beam injection. At least one of the capillary channels or each capillary channel may include an internal structure 19 as illustrated.

[0078] Figure 4C shows that at least one of the capillary channels 11 may have a flattened shape, so that the gas sub-flow in the respective capillary channel has a slot shape perpendicular to the irradiation path 5. The inner diameter of the capillary channel 11 along the irradiation path 5 is smaller than the inner diameter of the capillary channel 11 perpendicular to the irradiation path 5.

[0079] Figure 5 illustrates details of an embodiment of the gas supply control device 20 (gas system) in part. In particular, Figure 5 shows a portion of the gas supply control device 20, which is configured for supplying a gas mixture to one of the capillary channels, for instance 11. Additionally, the embodiment of the gas control device 20 is adapted for fulfilling the task of the gas collection device 30, see Figure 1. For gas supply to each of the capillaries, multiple structures of Figure 5 are provided, each being connected with one of the capillary channels.

[0080] With more details, three input sections 21 are provided for a connection of the gas supply control device 20 with the gas source device 220 (see Figure 1). Each input section 21 includes a valve 21A. The valves 21A can be adapted for a manual operation by a user of the plasma source device 100, or it may be driven by an external control device or the control loop device 240 (see Figure 1). By operating the valves 21A, the gas species, including for instance hydrogen, helium and nitrogen, can be mixed at a connector 21B of the input sections 21. Downstream of the connector 21B, a regulator/gauge unit 22 is arranged, followed by a mass flow controller 23. Downstream of the mass flow controller 23, a first reservoir 24 is arranged, which provides a gas buffer. The capillary channel 11 is connected with the downstream end of the first reservoir 24 via a solenoid valve 25, which is arranged for controlling the gas flow to the capillary channel 11. Additionally, a pressure or gas density of the gas flow supplied to the capillary channel 11 can be monitored with the pressure gauge 26.

[0081] For fulfilling the function of the gas collection device 30 (see Figure 1) the gas flowing from the capillary channel 11 is collected in a second reservoir 27 integrated in the gas supply control device 20. The second reservoir 27 is used as a second buffer, from which a bypass is provided back to the mass flow controller 23, so that the gas supplied to the capillary channel 11 can be reused. Alternatively, by operating an exhaust valve 28, the gas collected from the capillary channel 11 can be conducted to an external scroll pump, optionally with a nitrogen purge.

[0082] In operation, the valves 21A and 28 as well as the regulator/gauge unit 22 and the mass flow controller 23 and the solenoid valve 25 can be controlled, for instance with the control loop device 240 (see Figure 1).

[0083] Figure 6 illustrates an important advantage of the inventive technique. An energy spectrum (modulus squared of the spectral amplitude, I) of a plasma accelerator output (in this case, accelerated electron beam) with a conventional high-repetition-rate plasma accelerator is schematically shown in Figure 6A in an exemplary manner. The spectrum of energy E in a range from 2 MeV to 14 MeV is characterized by a broad, noisy shape. On the contrary, Figure 6B shows the spectrum of the plasma wave created according to the invention in the same energy range. Advantageously, a narrowed spectrum with an increased spectral amplitude (electron charge per energy unit), e.g. increased by a factor 10, is obtained. Moreover, the energy of the peak can be tuned tuning the geometry of the capillary channel device.

[0084] Advantageously, the invention enables fine control of the electron and X-ray beams from an ultra-compact laser driven plasma accelerator. Preferred applications of the invention are summarized in the following. Firstly, the plasma source device has applications in scientific research, where the use of it in commercial laser plasma accelerators allows researchers to conduct experiments, like e.g. electron beam diffraction, X-ray absorption spectroscopy, ultrafast X-ray imaging and/or positron and gamma ray production, usually performed at large electron beam or light source facilities in their own university-based laboratories. Furthermore, applications are available in the medical sector for medical imaging and cancer treatment. Applications in industry comprise e.g. industrial processing, industrial inspection and material investigations.

[0085] The features of the invention disclosed in the above description, the drawings and the claims can be of significance both individually as well as in combination or sub-combination for the realization of the invention in its various embodiments. The invention is not restricted to the preferred embodiments described above. Rather a plurality of variants and derivatives is possible which also use the inventive concept and therefore fall within the scope of protection. In addition, the invention also claims protection for the subject and features of the subclaims independently of the features and claims to which they refer.

Claims

1. Plasma source device (100), being configured for providing a localized gas volume (1) in a plasma accelerator apparatus (200), comprising

- a capillary channel device (10) being arranged for guiding and confining a gas flow (2), wherein the capillary channel device (10) comprises an irradiation port (10A) being arranged for receiving laser light (3) along an irradiation direction (z) deviating from an axial flow direction (x) of the gas flow (2) in the capillary channel device (10) and an output port (10B) being aligned with the irradiation port (10A) and being arranged for an output of a plasma accelerator output (4), including electron and/or X-ray beams, wherein the gas volume (1) is provided by gas of the gas flow (2) traversing an irradiation path (5) between the irradiation port (10A) and the output port (10B),

characterized in that

- the capillary channel device (10) comprises multiple capillary channels (11, 12), wherein each of the capillary channels (11, 12) has two radial pinholes (13),
- the capillary channels (11, 12) are arranged side by side with all pinholes (13) being aligned in series so that the irradiation path (5) through the capillary channel device (10) along the irradiation direction (z) is provided, wherein a first pinhole (13) of a first capillary channel (11) within the capillary channel device (10) is the irradiation port (10A) and a last pinhole (13) of a last capillary channel (12) within the capillary channel device (10) is the output port (10B), and
- the gas volume (1) comprises multiple gas sections (14, 15) arranged along the irradiation path (5), wherein each of the gas sections (14, 15) is provided with predetermined gas parameters by one of the capillary channels (11, 12).

2. Plasma source device according to claim 1, wherein

- the capillary channels (11, 12) are arranged for providing the gas sections (14, 15) with the gas parameters including at least one of gas species, gas density and gas density gradient along the irradiation path (5).

3. Plasma source device according to one of the foregoing claims, further comprising

- a gas supply control device (20) being capable of coupling the capillary channel device (10) with a gas source device (220), wherein
- the gas supply control device (20) is configured for adjusting the gas parameters of the gas sections (14, 15) and/or an overall areal density of the gas sections (14, 15) along the irradiation path (5).

4. Plasma source device according to claim 3, wherein

- the gas supply control device (20) is configured for an in-situ and operando control of the gas parameters of the gas sections (14, 15) and/or the overall areal density of the gas sections (14, 15) along the irradiation path (5).

5. Plasma source device according to one of the foregoing claims, wherein

- the pinholes (13) and/or inner diameters (d) along the irradiation path (5) of at least one of the capillary channels (11, 12) have different dimensions compared with the pinholes (13) and/or inner diameters (d) along the irradiation path (5) of at least one neighbouring capillary channel (11).

6. Plasma source device according to one of the foregoing claims, wherein

- the pinholes (13) of at least one of the capillary channels (11, 12) have different diameters so that the gas section within the at least one of the capillary channels (11, 12) has a gas density gradient along the irradiation path (5).

7. Plasma source device according to one of the foregoing claims, wherein

- the capillary channels (11, 12) are configured for providing the gas sections (14, 15) such that the gas parameters in a first gas section (14) are selected for creating an injection of electrons in a plasma wave formed in the ionised gas section in response to the irradiation of the gas with the laser light (3) and that the gas parameters in a subsequent second gas section (15) are selected for accelerating the electrons in response to the further irradiation of the gas with the laser light (3).

8. Plasma source device according to one of the foregoing claims, comprising at least one of the features

- the capillary channels (11, 12) and the pinholes (13) are arranged with an alignment such that the irradiation path (5) is perpendicular to a capillary gas flow direction (x) of each capillary channel (11, 12),
- at least two of the capillary channels (11, 12) are arranged with capillary gas flow directions (x) inclined relative to each other, and
- at least two of the capillary channels (11, 12) are arranged with parallel capillary gas flow directions (x).

9. Plasma source device according to one of the foregoing claims, comprising at least one of the features

- at least two of the capillary channels (11, 12) contact each other along the irradiation path (5),
- at least two of the capillary channels (11, 12) are spaced from each other along the irradiation path (5),
- at least two of the capillary channels (11, 12) are provided as channels (11, 12) in a solid block (16), in particular being made of sapphire.

10. Plasma source device according to one of the foregoing claims, wherein

- at least one of the capillary channels (11, 12) has a flattened shape or an elongated shape along the irradiation path (5).

11. Plasma source device according to one of the foregoing claims, wherein

- the capillary channel device (10) comprises 2 to 5 capillary channels (11, 12).

12. Plasma accelerator apparatus (200) being configured for creating a plasma accelerator output (4), including electron and/or X-ray beams, comprising

- a laser source device (210) being arranged for creating laser light (3),
- a gas source device (220) being arranged for providing at least one gas species, and
- the plasma source device (100) according to one of the foregoing claims, wherein
- the plasma source device (100) is coupled with the gas source device (220), and
- the laser source device (210) is arranged for irradiating the gas volume (1) provided by the gas sections (14, 15) in the irradiation path (5).

13. Plasma accelerator apparatus according to claim 12, further comprising

- a sensor device (230) being arranged for detecting at least one output parameter of the plasma accelerator output (4) leaving the output port (10B), and
- a control loop device (240) being arranged for tuning the plasma source device (100) in dependency on a sensor signal of the sensor device (230).

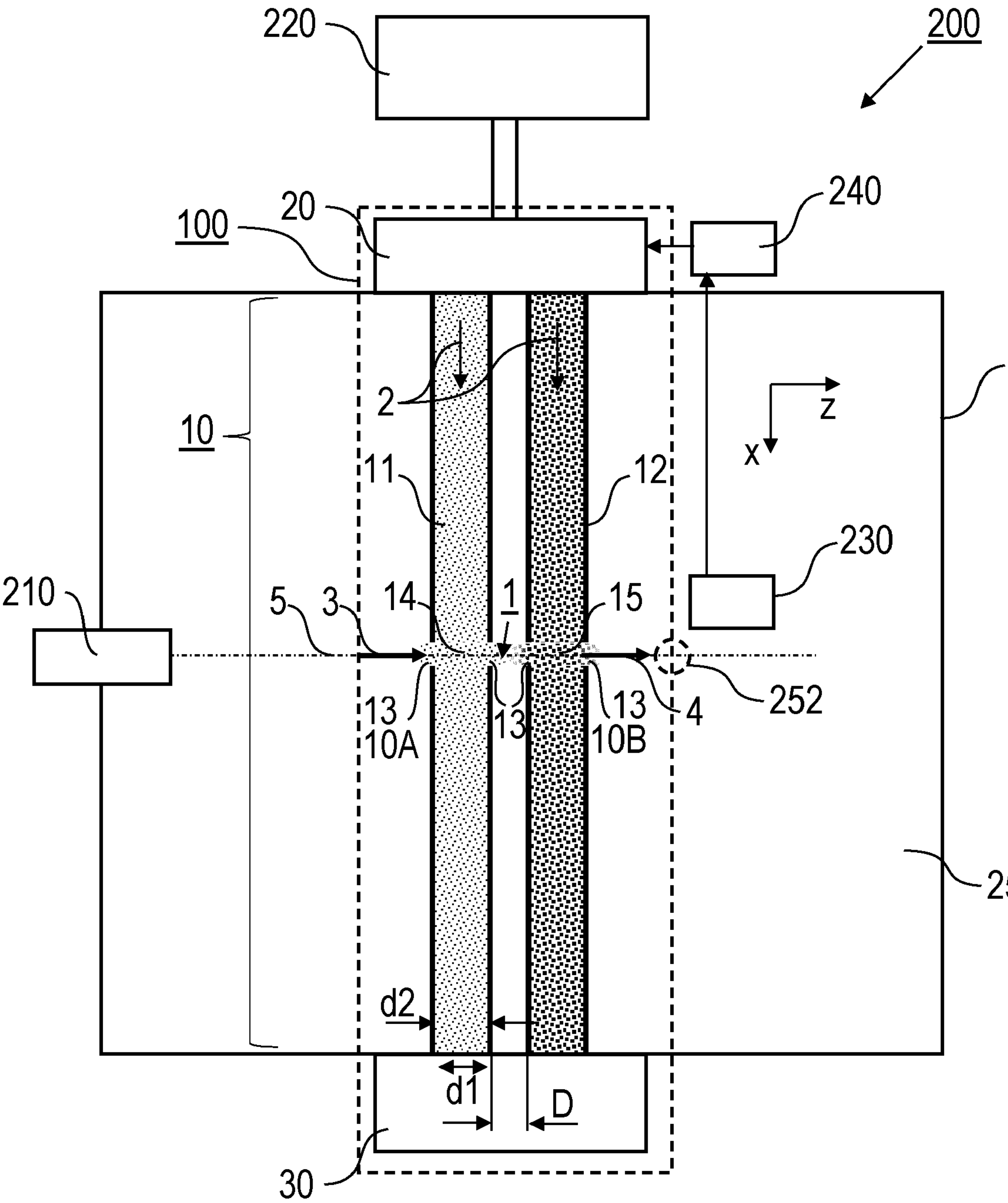
14. Method of creating a plasma accelerator output (4), including electron and/or X-ray beams, wherein the plasma source device (100) according to one of the claims 1 to 11 and the plasma accelerator apparatus (200) according to one of the claims 12 and 13 is used, comprising the steps of

- providing a localized gas volume (1) of at least one gas species with the plasma source device (100), said gas volume (1) including the multiple gas sections (14, 15) along the irradiation path (5) of the plasma source device (100),
- irradiating the gas sections (14, 15) along the irradiation path (5) with laser light (3), including injecting electrons into a plasma wave formed in the gas section and accelerating the electrons, and
- output of the plasma accelerator output (4) to be obtained.

15. Method according to claim 14, including further steps of

- detecting at least one output parameter of the plasma accelerator output (4) leaving the output port (10B), and

- tuning the plasma source device (100) in dependency on the detected at least one output parameter of the at least one plasma accelerator output (4).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200
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FIG. 1

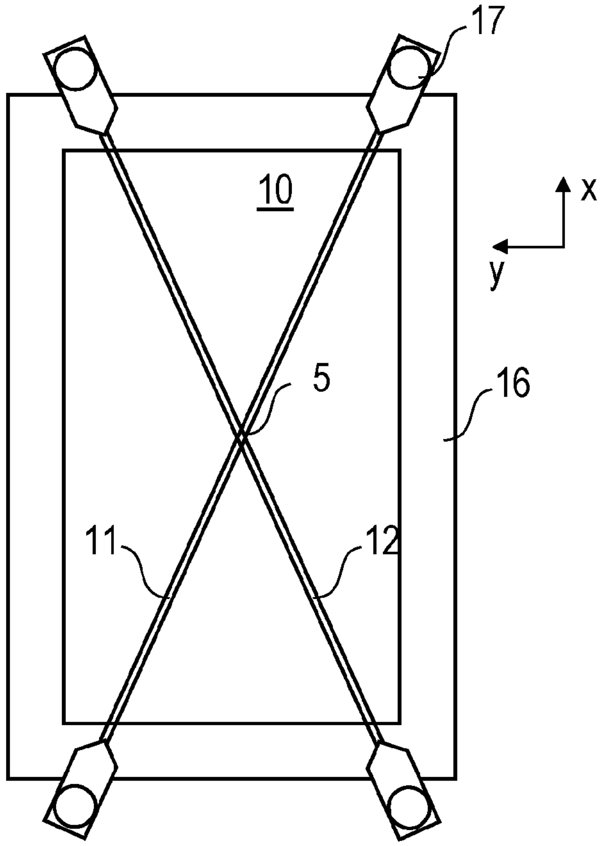

FIG. 2

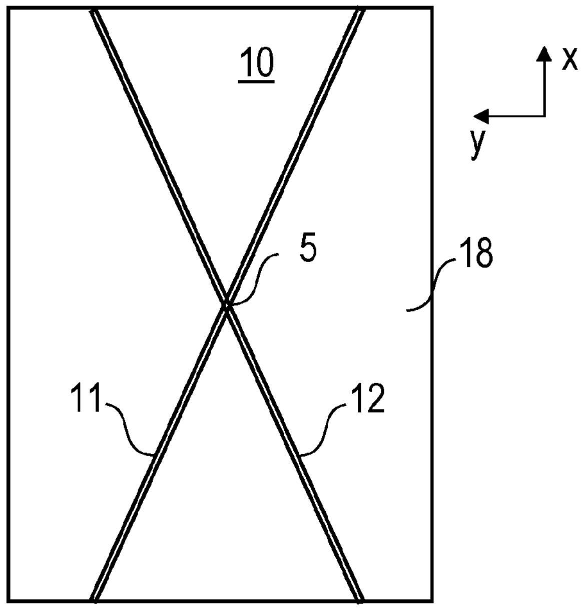

FIG. 3

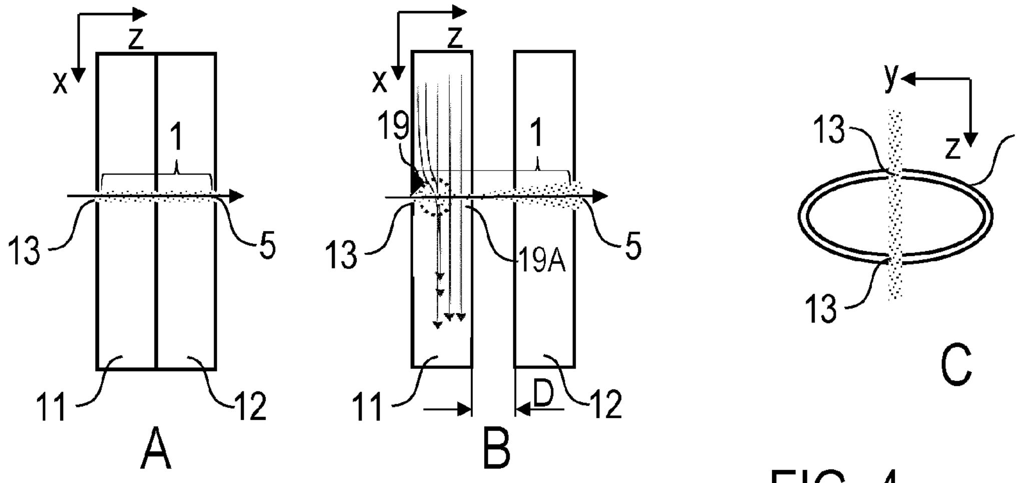

FIG. 4

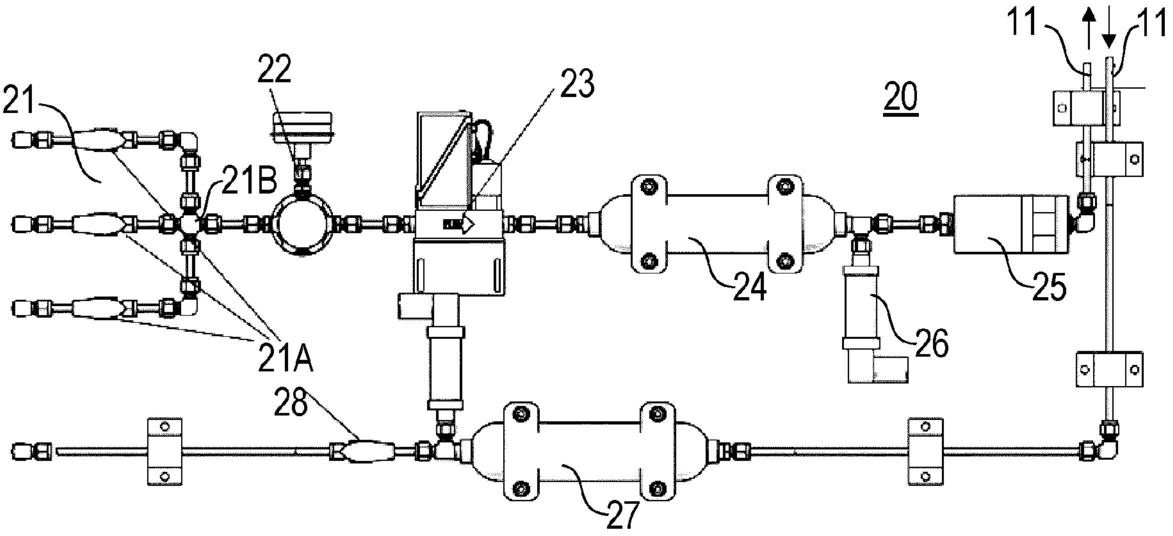

FIG. 5

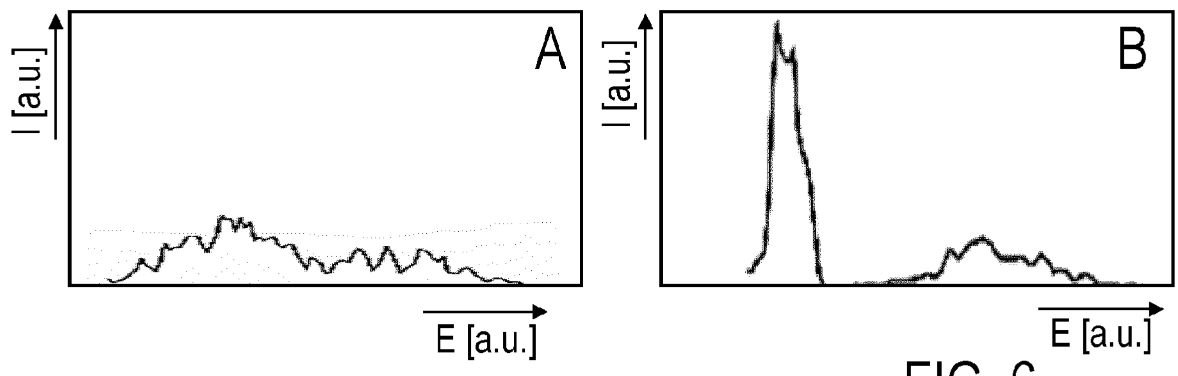

FIG. 6

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EUROPEAN SEARCH REPORT

Application Number
EP 23 18 7862

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	J. S. LIU ET AL: "All-Optical Cascaded Laser Wakefield Accelerator Using Ionization-Induced Injection", PHYSICAL REVIEW LETTERS, vol. 107, no. 3, 1 July 2011 (2011-07-01), XP055669811, US ISSN: 0031-9007, DOI: 10.1103/PhysRevLett.107.035001	1-5,7-9, 11-15	INV. H05H15/00
A	* abstract; figures 1,2,3,4 * * page 1, column 2 - page 2, column 1 * * page 3 - page 4 * -----	6,10	
X	EP 3 216 324 B1 (ECOLE POLYTECH [FR]; ECOLE NAT SUPERIEURE DE TECHNIQUES AVANCEES [FR]) 27 October 2021 (2021-10-27) * abstract; claim 3; figures 2,6 * -----	1,9,11, 12,14	
A,D	B. FARACE: "Confined Continuous-Flow Plasma Source For High-Average-Power Laser Plasma Acceleration", ARXIV:2205.02763V1, 5 May 2022 (2022-05-05), XP093119141, * abstract; figure 2 * -----	1,12,14	TECHNICAL FIELDS SEARCHED (IPC)
			H05H
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The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
The Hague	24 January 2024	Crescenti, Massimo

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EPO FORM 1503 03.82 (P04C01)

CATEGORY OF CITED DOCUMENTS

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EUROPEAN SEARCH REPORT

Application Number
EP 23 18 7862

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Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
A	US 2010/084494 A1 (KRISHNAN MAHADEVAN [US]) 8 April 2010 (2010-04-08) * abstract; figures 5a,5b,6a * -----	1,12,14	

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Place of search	Date of completion of the search	Examiner
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ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO.

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24-01-2024

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