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(54) **HIGH FLUX, NARROW BANDWIDTH COMPTON LIGHT SOURCES VIA EXTENDED LASER-ELECTRON INTERACTIONS**

COMPTON-LICHTQUELLEN MIT HOHEM FLUSS UND SCHMALER BANDBREITE DURCH ERWEITERTE LASER-ELEKTRONEN-WECHSELWIRKUNGEN

SOURCES DE LUMIÈRE À EFFET COMPTON, À FLUX ÉLEVÉ ET À LARGEUR DE BANDE ÉTROITE VIA DES INTERACTIONS LASERS-ÉLECTRONS ÉTENDUES

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- **LUO W ET AL: "X-ray generation from slanting laser-Compton scattering for future energy-tunable Shanghai Laser Electron Gamma Source", APPLIED PHYSICS B ; LASERS AND OPTICS, SPRINGER, BERLIN, DE, vol. 101, no. 4, 23 June 2010 (2010-06-23) , pages 761-771, XP019865475, ISSN: 1432-0649, DOI: 10.1007/S00340-010-4100-0**

EP 2 735 063 B9

Description

[0001] The United States Government has rights in this invention pursuant to Contract No. DE-AC52-07NA27344 between the U.S. Department of Energy and Lawrence Livermore National Security, LLC, for the operation of Lawrence Livermore National Laboratory.

BACKGROUND OF THE INVENTION

Field of the Invention

[0002] The present invention relates to Compton light sources, and more specifically, it relates to pulse formats and interaction geometries that produce ultra narrow bandwidth (10E-3 or lower) and high beam flux quasi-mono-energetic x-rays and gamma rays.

Description of Related Art

[0003] Gamma-rays and x-rays can be produced via laser Compton scattering in which an energetic laser pulse collides with a relativistic bunch of electrons which have been produced by a particle accelerator. The output of this interaction is up-shifted light that is directed in the direction of the electron beam. The energy of the up-shifted light in a head-on collision is equal to the incident laser photon energy multiplied by 4 times the normalized energy of the electron squared. Up-shifts of a million can be created by electrons with energy of a few hundred MeV. The scattered light is polarized and tunable by changing either the color of the laser photon or the energy of the electron bunch. The output is polychromatic but with a spectrum that is angle correlated. By passing the beam through a narrow aperture a quasi-mono-energetic beam can be created with a bandwidth that is dependent linearly upon the laser bandwidth, linearly upon the electron bunch energy spread and upon the focusing geometry of the electron beam and the laser beam.

[0004] Laser-Compton light sources have been constructed primarily to create short duration x-rays or tunable, relatively broadband x-rays. In these systems, the laser pulse duration is of order or shorter in duration than that of the electron bunch and both are focused to a small spot in order to maximize the interaction and the total photon yield. The Compton scattering cross section (also known as the Thomson cross section) is very small, ~ 6×10^{-25} cm^2. Note in Compton scattering, of the order of 10^{19} laser photons interact with the order of 10^{10} electrons to produce of the order of 10^{10} up-scattered x-rays or gamma-rays. To first order, no laser photons are used. Because of the tight focus, the longitudinal transit time of the electrons through the focal region is typically of order the duration of the electron bunch. In this scenario the laser pulse and electron bunch timing must be carefully adjusted so that both pulses overlap at a common focus in space. Furthermore both the laser pulse energy and the electron beam charge are made as high as practical to increase the probability of interaction and the flux of the outgoing beam. This process can also be used to make gamma-rays simply by increasing the energy of the electron beam. The generation of gamma-rays can be more efficient in that higher energy electron beams can be focused to smaller spots, thus producing more up-scattered photons. Because of the large laser bandwidth used, the relatively large energy spread of the high charge electron bunches and the tight focusing geometries employed in these systems, the fractional bandwidth of typical laser Compton light sources has been of order 10%. (Measurements from systems at Duke University, the Japanese Atomic Research Agency in Japan and at Lawrence Livermore National Laboratory (LLNL) are in this range)

[0005] However for many gamma-ray applications the primary beam quality of interest is not beam pulse duration or even total beam flux but is instead gamma-ray bandwidth. It is desirable to provide gamma-rays with fractional bandwidths of 10E-3 or less for use to uniquely excite narrow band (10E-6) nuclear resonances that are unique signatures of isotopes. By monitoring the absorption of resonance photons from such a laser-Compton gamma-ray beam, one can detect, assay or image the presence of specific isotopes in complex systems. Applications include homeland security, nuclear fuel management, industrial materials processing and medical therapy and radiography.

[0006] Luo W. et al. : "X-ray generation from slanting laser-Compton scattering for future energy-tunable Shanghai Laser Electron Gamma Source", APPLIED PHYSICS B; LASERS AND OPTICS, SPRINGER, BERLIN, DE, relates to generation of energy-tunable, bright, short-pulse X/γ-ray sources, which are required in various research fields. As described, Laser-Compton scattering (LCS) is considered to be one of the most promising methods to implement this kind of X/γ-ray source. At the 100-MeV LINAC of Shanghai Institute of Applied Physics, a 2-J, 8-ns, 1064-nm, Q-switched Nd:YAG laser is brought to a slanting collision at 40° (44°) with an 112-MeV, 0.9-ns (rms) relativistic electron beam. Further, the LCS X-ray energy spectrum with a peak energy of 31.73 $\pm 0.22_{stat} \pm 1.64_{syst}$ keV and a peak width (rms) of 0.74 $\pm 0.26_{stat} \pm 0.03_{syst}$ keV was measured. This preliminary investigation was carried out to understand the feasibility of developing an energy-tunable X/γ-ray source. Based on this study, the future Laser Electron Gamma Source (SLEGS) at the Shanghai Synchrotron Radiation Facility (SSRF) can be constructed to be not only an energy-tunable γ-ray source by guiding the laser incident angle from laser-Compton scattering, but also a high flux (~10^{10} photons/s or even higher) γ-ray source by adding super-cavity.

[0007] US 6,332,017 B1 relates to a system for generating tunable pulsed monochromatic X-rays comprising a tabletop terawatt laser delivering 10 Joules of energy in 10 ps at a wavelength of 1.1 microns. The light beam from the laser is counter-propagated against an electron beam produced by a linear accelerator. X-ray photons are generated by inverse Compton scattering that occurs as a consequence of the "collision" that occurs between the electron beam and IR photons generated by the laser.The system uses a novel pulse structure comprising, in a preferred embodiment, a single micropulse. The LINAC is configured to generate an electron beam having 1 nanocoulomb of charge in a microbunch having a pulse length of about 5 picoseconds or less (or an electron beam brightness of 1012 A/m2-radian2@ 500 A). A beam alignment sub-system is used at the laser beam-electron beam interaction zone and directs the X-ray beam, in a preferred embodiment, through a beryllium window and onto mosaic crystals which divert the beam into a beam transport system toward the imaging target.

SUMMARY OF THE INVENTION

[0008] The invention produces high flux beams of bright, tunable, polarized quasimonoenergetic x-rays or gamma-rays via laser-Compton scattering x-ray or gamma-ray. An electron source generates a train of spaced electron bunches and an RF linear accelerator accelerated the electron bunches into a laser-electron beam interaction region. The transit time of each of the accelerated electron bunches through the laser-electron beam interaction region is both greater than the duration of the accelerated electron bunch and greater than the spacing between electron bunches. A laser system is adapted to produce a laser pulse having a duration at least as long as a transit time of the laser pulse through the laser-electron beam interaction region. The laser system is arranged so that the laser pulse traverses the laser-electron beam interaction region to interact with all of the accelerated electron bunches of the train. In some embodiments, the duration of the laser pulse is substantially equal to at least a total length of the train of spaced electron bunches so that a single pass of the laser pulse through the laser-electron beam interaction region interacts with all of the accelerated electron bunches of the train. In other embodiments, the duration of the laser pulse is substantially equal to a sub-multiple of a total length of the train of spaced electron bunches. The laser system is arranged to recirculate the laser pulse through the laser-electron beam interaction region for a predetermined number of passes equal to an inverse of the sub-multiple. The spacing frequency of the electron bunches can the same as or correlated to the RF frequency of the RF linear accelerator so that an electron bunch is present for every cycle of said RF frequency.

[0009] The invention is useful in the generation of narrowband, high flux mono-energetic gamma-rays and x-rays. Uses of the gamma-rays include isotope specific material detection, assay and imaging via excitation of nuclear resonance fluorescence, photo-fission of materials, medical imaging and therapy. X-ray uses include precision radiography, low dose radiography and targeted radio-therapy

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] The accompanying drawings, which are incorporated into and form a part of the disclosure, illustrate embodiments of the invention and, together with the description, serve to explain the principles of the invention.

Figure 1 shows the basic components of an embodiment of the invention.

Figures 2 through 6 illustrate aspects of the operation of an embodiment of the invention.

DETAILED DESCRIPTION OF THE INVENTION

[0011] The invention provides a new pulse format and interaction geometry that produces both ultra-narrow bandwidth (10E-3 or lower) and high beam flux quasi-mono-energetic x-rays and gamma-rays. The basic idea has three components: 1) distribute the charge of the electron bunch over many smaller charge bunches, 2) increase the focal spot size of the interaction so that the transit time of the electron bunch through the interaction region is significantly longer than the duration of the electron bunch and significantly longer than the spacing between successive electron bunches and 3) use a long duration laser pulse whose pulse duration is chosen to be as long or longer than the transit time of the laser through the interaction region. In this way one laser pulse can interact with many (e.g., 100 or more) electron bunches at one time thus producing a high flux (in fact higher than the conventional geometry if the laser energy is adjusted correctly). Furthermore the long duration laser pulse has narrower bandwidth than short duration laser pulses thus the gamma-ray bandwidth contribution from the laser is reduced (typically by a 1000 fold). Furthermore because the bunch charge of the electrons is smaller, the space charge dependent energy dispersion of the bunch is smaller and the energy spread is smaller, thus the e-beam contribution to the gamma-ray bandwidth is reduced (typically by a factor of 10 or more). Further, because the bunch charge is smaller, the quality of the electron beam is higher, i.e., the emittance which is typically proportional to square root of charge is lower. Lower emittance beams can be focused to a given spot size for a longer length. This leads to a longer and more collimated laser-electron beam interaction which in turn reduces the focusing contribution to gamma-ray bandwidth (typically another factor of 10). Finally because the electron beam and laser foci are relatively large and the laser pulse duration is relatively long, the intensity of the laser pulse in the interaction region is reduced (100 fold or more) and thus non-linear effects which tend to broaden the bandwidth of gamma-ray sources are also reduced dramatically. One might not need to focus the electron beam at all out of the accelerator, only the laser beam. In some x-band structures the beam diameter can be 100 microns right out of the device and this is approximately the laser diameter in the focal region. Not having to focus the electron beam means that there is no need for focusing quadrupoles, thus saving space and complexity.

[0012] Figure 1 shows the basic components of an embodiment of the invention. A laser system in enclosure **10** is configured to drive a photo-gun of a linear accelerator **12.** A fiber optic **14** (or other bulk optical arrangement) is provided to transport light from the laser system to an amplifier in enclosure **16.** Light from the amplifier is then directed to a frequency conversion means in enclosure **17** to convert the light to an appropriate UV wavelength to drive the photo-gun. The e-beam output from the linear accelerator **12** is directed into an interaction chamber **18.** The interaction chamber includes an interaction region and re-circulating optics and discussed below. An e-beam deflector **20** is provided to direct any residual e-beam toward a beam stop **22.**

[0013] Referring still to Figure 1, a laser system in enclosure **30** is configured to provide a long pulse length laser pulse which is directed by a fiber optic **32** (or other bulk optical arrangement) to an amplifier in enclosure **34.** The beam from amplifier **34** is directed by mirror **35** through a beam splitter and through a frequency converter (the frequency converter could be omitted and the direct laser beam used if lower energy x-rays or gamma-rays are desired) in interaction chamber **18** and into the oncoming e-beam. The laser beam interacts with the e-beam to produce x-rays or gamma rays.

[0014] Figures 2 through 7 illustrate aspects of the operation of an embodiment of the invention. Laser system **10** provides mode-locked pulses **100** into fiber optic **14.** Pulses **100** are provided at a frequency that is matched to the RF frequency of the linear accelerator **12,** nominally 10 GHz. Alternately, an approximately 10 GHz laser pulse train can be generated by modulation of a CW laser via high speed electro-optic components driven by the accelerator RF frequency or a multiple thereof. Subsequent non-linear effects can be used to reduce the pulse duration of the individual 10 GHz pulses to durations required to produce bright electron bunches from the photocathode, e.g., approximately 1 ps. Synchronization of the mode locked laser and the accelerator RF must be on the order of a fraction of the pulse duration of the pulse hitting the cathode, i.e., nominally 100 fs accuracy. The wavelength of the light from laser system **10** is 1053 nm in this embodiment.

[0015] Figure 3 shows pulses **100** passing through amplifier enclosure **16** and then through conversion means enclosure **17** from which pulses **100** are directed into linear accelerator **12.** The wavelength used to drive the photo-gun is in the UV and depends upon the cathode material used. If the cathode material is copper, then the wavelength would be the 4th harmonic of 1053 nm. If the cathode material is magnesium, then the wavelength would be the 3rd harmonic of 1053 nm. The pulse duration is nominally a 2 ps square pulse with a 100 fs rise and fall. Other pulse shapes are also possible and depend upon the cathode design and cathode dynamics. The laser drive pulse repetition rate is the same as the RF of the accelerator. The inventors have used the SLAC x-band standard of 11.424 GHz but the invention would work for an arbitrary repetition rate. If the repetition rate is too slow, then the spacing of the electron bunches becomes too big and might be larger than the transit time through the interaction region. Higher repetition is possible but good accelerator structures beyond about 12 GHz have not yet been demonstrated. The energy of the laser drive pulses depends upon the cathode material quantum efficiency. For copper, about 50 microJoules per pulse are needed. Magnesium is 10x more efficient and thus, only around 5 microJoules are needed. These energies may vary by factors of 2 to 4 depending upon the accelerator structure. Basically, as much charge is placed in each bunch as possible without destroying the electron beam emmittance. The quality of the gammas scale as the charge/emmittance^2, but the total flux is proportional to the charge. Amplifier 16 can in principle be done with either a bulk amplifier or a fiber amplifier or a combination of both. Because copper cathodes require more energy, it is likely that we would need a bulk amplifier at the end after the fiber preamplifiers. If a magnesium cathode is used, the pulses can be generated using only fiber laser amplifiers (obviously an advantage). The photo-gun is not shown, but is known in the art. One embodiment photo gun provide 25 pC charge electron bunches. The photogun must produce electrons in each RF bucket (i.e., each acceleration cycle) that are nominally the same charge, with identical energy and beam emmittance. For purposes of this embodiment, the energies are identical if there is substantially no variation beyond about 10E-3. When the invention is used to make x-rays, a larger variation from bunch to bunch is tolerable.

[0016] In single bunch mode at x-band frequencies, the bunch charge should be ~250 pC. An embodiment of the invention in the multi-bunch mode of this invention is set up to operate at nominally 1/10th the bunch charge, i.e., 25 pC. Electron perturbations and issues in the accelerator scale in proportion to the square of the bunch charge so for the multi-bunch mode, these issues will be nominally 100x smaller.

[0017] Referring still to Figure 3, laser system **30** is a Nd:YAG laser configured to provide a long pulse **110** at a wavelength of about 1064 nm. The laser system **30** is configured to provide sufficient energy and high average power. The intensity is in the joule per pulse range for a 10 ns pulse. The bandwidth is less than the desired gamma-ray bandwidth, typically 10E-3. This bandwidth is easy for a 10 ns pulse. Note that the use of narrower bandwidth is not beneficial because the interaction geometry also broadens the gamma-ray bandwidth by of order 10E-3. The exact laser pulse energy is dependent upon the interaction region focal spot size and length (the spot size and length are tied to each other via diffraction relations). Embodiments of a symmetric mode Compton source known as T-REX had a small spot size (~20 microns) and short confocal interaction region (cm's). The present embodiment uses focal spots of >100 microns and interaction lengths of order a meter or greater. As sown in Figure 4, the laser pulse energy of pulse **110** is amplified by the amplifier, which is configured to produce between 1 to 10 Joules.

[0018] As shown in Figure 5, after amplification, pulse **110** is directed into interaction chamber **18** where it passes through a the beamsplitter and the conversion element to then be reflected into the path of the oncoming electron bunches **118.** As shown in Figure 6, the pulse **110** is recirculated within the interaction chamber **18.** The laser pulse duration is chosen to be equal to the total length of the total electron bunch train (also known as the macro-bunch length) or some integer sub-multiple of the bunch train length. One could artificially create an 87.5 ns interaction with shorter duration laser pulses by collecting the laser light after the interaction region and re-circulating it to interact with subsequent electron bunches. The cavity can be constructed out of high reflective mirrors, one polarizer and a pockels cell. Pulse **110** consisting of polarized light can be injected into the cavity via the polarizer. The polarization is then be rotated 90 degrees by the Pockels cell and the light would is trapped. The scattered light is polarized and tunable by changing either the color of the laser photon or the energy of the electron bunch. The output is polychromatic but with a spectrum that is angle correlated. By passing the beam through a narrow aperture a quasi-mono-energetic beam can be created with a bandwidth that is dependent linearly upon the laser bandwidth, linearly upon the electron bunch energy spread and upon the focusing geometry of the electron beam and the laser beam. As shown in Figure 7, the pulse **110** continues to circulate through the cavity to interact with the remainder of the electron bunches.

[0019] In practice, this configuration has been dubbed the "fill every bucket" configuration since ultimately one would put electrons in every "RF" bucket of the accelerator structure, i.e., there would be one electron bunch for every cycle of the RF frequency driving the accelerator. Because the length of the focal region is constrained by geometrical optics and free space diffraction of laser beams, in practice the laser-electron interaction is not a free parameter and is typically 1 meter in length. For this reason it is advantageous to operate the accelerator at as high an RF frequency as practical. Accelerator operation is limited by field-driven breakdown of accelerator structures and this in turn depends upon frequency. The highest practical frequency that accelerators currently operate is x-band (nominally 12 GHz). The invention has been designed with devices that operate in the x-band at 11.424 GHz. At this frequency the spacing between electron bunches is 87.5 ps or approximately 3 cm separation in space. Thus a 1 meter focal interaction region will contain at any one time approximately 34 electron bunches. The laser pulse duration can be chosen to be equal to the total length of the total electron bunch train (also known as the macro-bunch length) or some integer sub-multiple of the bunch train length. For 1000 bunches, the laser pulse duration is approximately 87.5 ns. One could artificially create an 87.5 ns interaction with shorter duration laser pulses by collecting the laser light after the interaction region and recirculating it to interact with subsequent electron bunches. In practice, the use of high frequency RF accelerators also results in smaller transverse electron beam size (typically 100 microns in diameter). The size of the electron beam exiting the accelerator is nearly the focal spot size of the laser in the interaction region. As a result, the required electron beam focusing in the interaction region is both small and easy to perform.

[0020] The invention provides many advantages in addition to those described above. The use of 1000x and longer duration laser pulses in the interaction region reduces dramatically the potential for laser damage on the vacuum windows through which the laser enters the interaction region, the mirror by which the laser is directed in the interaction region and the optics by which the laser is focused into the interaction region. Laser pulses of such long duration enable the use of simpler and less expensive refractive optics for focusing of the laser pulse in the interaction region. One present embodiment uses off axis parabolic mirrors for focusing. These longer duration laser pulses dramatically (1000x reduction) reduce the timing requirements for the laser relative to the electron bunch. The use of low charge electron bunches enables simpler beam deflection structures in the accelerator, which helps eliminate dark current electrons and dark current sources of high energy background photons. These low charge electron bunches reduce the energy requirements on the photo-gun drive laser that creates the electrons at the beginning of the accelerator and is compatible with existing, robust fiber laser technology. The use of long pulse lasers for the interaction laser reduces the complexity of the interaction laser system by eliminating the need for chirped pulse amplification. The use of larger interaction spot sizes and longer interaction laser-electron interaction regions creates a significantly more collimated gamma-ray or x-ray output (10 microradians or less for the narrowest bandwidth). The collimated output of this geometry is readily compatible with gamma-ray and x-ray lens technology as well as with narrowband gamma-ray spectrometer technology. Gamma-rays produced by this geometry can have a fractional bandwidth of 10E-3 or less. The use of this invention with lower energy accelerators, e.g., 40 MeV machines, allows the production of extremely high flux, tunable x-ray radiation.

[0021] The foregoing description of the invention has been presented for purposes of illustration and description and is not intended to be exhaustive or to limit the invention to the precise form disclosed. Many modifications and variations are possible in light of the above teaching. The embodiments disclosed were meant only to explain the principles of the invention and its practical application to thereby enable others skilled in the art to best use the invention in various embodiments and with various modifications suited to the particular use contemplated. The scope of the invention is to be defined by the following claims.

Claims

1. An x-ray or gamma-ray source having:

   - an electron source (10) configured in operation to generate a train of spaced electron bunches (118);
   - an RF linear accelerator (12) adapted to accelerate said electron bunches (118), which are directed along a path into a laser-electron beam interaction region; and
   - a laser system (30) adapted to produce a laser pulse (110), the laser system is arranged so that the laser pulse is reflected into said path of the oncoming electron bunches to interact with the electron bunches, so that the laser-electron beam interaction region extends along said path,

   characterized in that:

   the transit time of each of the accelerated electron bunches through the laser-electron beam interaction region is both greater than the duration of the accelerated electron bunch and greater than the spacing between electron bunches; the laser system adapted to produce a laser pulse having a duration at least as long as a transit time of the laser pulse through the laser-electron beam interaction region,
   wherein the duration of the laser pulse is either:

   equal to the total length of the train of spaced electron bunches so that a single pass of the laser pulse through the laser-electron beam interaction region interacts with all of the accelerated electron bunches of the train; or
   some integer sub-multiple of the length of the train of the spaced electron bunches, and the laser system is arranged to recirculate the laser pulse through the laser-electron beam interaction region for a predetermined number of passes equal to an inverse of the sub-multiple;

   and thereby produce high flux beams of bright, tunable, polarized quasi-monoenergetic x-rays or gamma-rays via laser-Compton scattering.

2. The x-ray or gamma-ray source of claim 1, wherein the spacing frequency of the electron bunches (118) is the same as or correlated to the RF frequency of the RF linear accelerator so that an electron bunch is present for every cycle of said RF frequency.

3. The x-ray or gamma-ray source of claim 1, wherein said RF linear accelerator (12) is operated in the x-band.

4. The x-ray or gamma-ray source of claim 1, wherein said accelerator (12) is operated nominally at about 12 GHz.

5. The x-ray or gamma-ray source of claim 1, wherein said accelerator (12) is operated nominally at about 11.424 GHz.

6. The x-ray or gamma-ray source of claim 1, wherein said gamma-rays comprise a fractional bandwidth of 10E-3 or less.

7. The x-ray or gamma-ray source of claim 1, wherein said electron source comprises a photo-gun.

8. The x-ray or gamma-ray source of claim 7, wherein said photo-gun is driven by a laser that operates at the RF frequency of the RF linear accelerator.

9. A method for producing high flux beams of bright, tunable, polarized quasi-monoenergetic x-rays or gamma-rays via laser-Compton scattering through the use of an electron source (10), an RF linear accelerator (12) and a laser system (30), the method **characterized by**:

   - generating, with the electron source, a train of spaced electron bunches (118);
   - accelerating, with the RF accelerator (12), said electron bunches, which are directed along a path into a laser-electron beam interaction region; and
   - producing, with the laser system (30), a laser pulse (110), the laser system is arranged so that the laser pulse is reflected into said path of the oncoming electron bunches to interact with the electron bunches, so that the laser-electron beam interaction region extends along said path,

   characterized in that:

   the transit time of each of the accelerated electron bunches through the laser-electron beam interaction region is both greater than the duration of the accelerated electron bunch and greater than the spacing between electron bunches; the laser system adapted to produce a laser pulse having a duration at least as long as a transit time of the laser pulse through the laser-

electron beam interaction region,
wherein the duration of the laser pulse is either:

equal to the total length of the train of spaced electron bunches so that a single pass of the laser pulse through the laser-electron beam interaction region interacts with all of the accelerated electron bunches of the train; or
some integer sub-multiple of the length of the train of the spaced electron bunches, and the laser system is arranged to recirculate the laser pulse through the laser-electron beam interaction region for a predetermined number of passes equal to an inverse of the sub-multiple;

and thereby produce high flux beams of bright, tunable, polarized quasi-monoenergetic x-ray or gamma-rays via laser-Compton scattering.

10. The method of claim 9, wherein the spacing frequency of the electron bunches (118) is the same as or correlated to the RF frequency of the RF linear accelerator so that an electron bunch is present for every cycle of said RF frequency.

11. The method of claim 9, wherein said RF linear accelerator (12) is operated in the x-band.

Patentansprüche

1. Röntgen- oder Gammastrahlenquelle, umfassend:

- eine Elektronenquelle (10), die im Betrieb konfiguriert ist, um eine Folge von beabstandeten Elektronenpaketen (118) zu erzeugen;
- einen HF-Linearbeschleuniger (12), der ausgestaltet ist, um die Elektronenpakete (118) zu beschleunigen, die entlang eines Pfades in eine Laser-Elektronenstrahl-Interaktionsregion geleitet werden; und
- ein Lasersystem (30), das ausgestaltet ist, um einen Laserimpuls (110) zu erzeugen, wobei das Lasersystem so ausgestaltet ist, dass der Laserimpuls in den Pfad der ankommenden Elektronenpakete reflektiert wird, um mit den Elektronenpaketen zu interagieren, so dass sich die Laser-Elektronenstrahl-Interaktionsregion entlang des Pfades erstreckt,

dadurch gekennzeichnet, dass:

die Transitzeit von jedem der beschleunigten Elektronenpakete durch die Laser-Elektronenstrahl-Interaktionsregion sowohl größer als die Dauer des beschleunigten Elektronenpakets als auch größer als der Abstand zwischen den Elektronenpaketen ist;
das Lasersystem ausgestaltet ist, um einen Laserimpuls mit einer Dauer zu erzeugen, die mindestens so lang ist wie eine Transitzeit des Laserimpulses durch die Laser-Elektronenstrahl-Interaktionsregion,
wobei die Dauer des Laserimpulses entweder:

gleich der Gesamtlänge der Folge von beabstandeten Elektronenpaketen, so dass ein einziger Durchgang des Laserimpulses durch die Laser-Elektronenstrahl-Interaktionsregion mit allen der beschleunigten Elektronenpakete der Folge interagiert; oder
ein ganzzahliges Teilvielfaches der Länge der Folge der beabstandeten Elektronenpakete, und das Lasersystem ausgestaltet ist, um den Laserimpuls durch die Laser-Elektronenstrahl-Interaktionsregion für eine vorbestimmte Anzahl von Durchgängen zu rezirkulieren, die gleich einer Inversen des Teilvielfachen ist;

und dadurch Strahlen mit hohem Fluss von hellen, abstimmbaren, polarisierten, quasi-monoenergetischen Röntgen- oder Gammastrahlen mittels Laser-Compton-Streuung erzeugt werden.

2. Röntgen- oder Gammastrahlenquelle nach Anspruch 1, wobei die Abstandsfrequenz der Elektronenpakete (118) gleich der HF-Frequenz des HF-Linearbeschleunigers ist oder mit dieser korreliert, so dass ein Elektronenpaket für jeden Zyklus der HF-Frequenz vorhanden ist.

3. Röntgen- oder Gammastrahlenquelle nach Anspruch 1, wobei der HF-Linearbeschleuniger (12) im X-Band betrieben wird.

4. Röntgen- oder Gammastrahlenquelle nach Anspruch 1, wobei der Beschleuniger (12) nominell bei etwa 12 GHz betrieben wird.

5. Röntgen- oder Gammastrahlenquelle nach Anspruch 1, wobei der Beschleuniger (12) nominell bei etwa 11,424 GHz betrieben wird.

6. Röntgen- oder Gammastrahlenquelle nach Anspruch 1, wobei die Gammastrahlen eine Teilbandbreite von 10E-3 oder weniger haben.

7. Röntgen- oder Gammastrahlenquelle nach Anspruch 1, wobei die Elektronenquelle eine Photo-Gun umfasst.

8. Röntgen- oder Gammastrahlenquelle nach Anspruch 7, wobei die Photo-Gun von einem Laser angetrieben wird, der mit der HF-Frequenz des HF-Linearbeschleunigers arbeitet.

9. Verfahren zum Erzeugen von Strahlen mit hohem Fluss von hellen, abstimmbaren, polarisierten, quasi-monoenergetischen Röntgen- oder Gammastrahlen mittels Laser-Compton-Streuung durch die Verwendung einer Elektronenquelle (10), eines HF-Linearbeschleunigers (12) und eines Lasersystems (30), wobei das Verfahren **gekennzeichnet ist durch**:

- Erzeugen, mit der Elektronenquelle, einer Folge von beabstandeten Elektronenpaketen (118);
- Beschleunigen, mit dem HF-Beschleuniger (12), der Elektronenpakete, die entlang eines Pfades in eine Laser-Elektronenstrahl-Interaktionsregion geleitet werden; und
- Erzeugen, mit dem Lasersystem (30), eines Laserimpulses (110) wobei das Lasersystem so ausgestaltet ist, dass der Laserimpuls in den Pfad der ankommenden Elektronenpakete reflektiert wird, um mit den Elektronenpaketen zu interagieren, so dass sich die Laser-Elektronenstrahl-Interaktionsregion entlang des Pfades erstreckt,

dadurch gekennzeichnet, dass:

die Transitzeit von jedem der beschleunigten Elektronenpakete **durch** die Laser-Elektronenstrahl-Interaktionsregion sowohl größer als die Dauer des beschleunigten Elektronenpakets als auch größer als der Abstand zwischen den Elektronenpaketen ist;
das Lasersystem ausgestaltet ist, um einen Laserimpuls mit einer Dauer zu erzeugen, die mindestens so lang ist wie die Transitzeit des Laserimpulses **durch** die Laser-Elektronenstrahl-Interaktionsregion,
wobei die Dauer des Laserimpulses entweder:

gleich der Gesamtlänge der Folge von beabstandeten Elektronenpaketen, so dass ein einziger Durchgang des Laserimpulses **durch** die Laser-Elektronenstrahl-Interaktionsregion mit allen der beschleunigten Elektronenpakete der Folge interagiert; oder
ein ganzzahliges Teilvielfaches der Länge der Folge der beabstandeten Elektronenpakete, und das Lasersystem ausgestaltet ist, um den Laserimpuls **durch** die Laser-Elektronenstrahl-Interaktionsregion für eine vorbestimmte Anzahl von Durchgängen zu rezirkulieren, die gleich einer Inversen des Teilvielfachen ist;

und dadurch Strahlen mit hohem Fluss von hellen, abstimmbaren, polarisierten, quasi-monoenergetischen Röntgen- oder Gammastrahlen mittels Laser-Compton-Streuung erzeugt werden.

10. Verfahren nach Anspruch 9, wobei die Abstandsfrequenz der Elektronenpakete (118) gleich der HF-Frequenz des HF-Linearbeschleunigers ist oder mit dieser korreliert, so dass ein Elektronenpaket für jeden Zyklus der HF-Frequenz vorhanden ist.

11. Verfahren nach Anspruch 9, wobei der HF-Linearbeschleuniger (12) im X-Band betrieben wird.

Revendications

1. Source de rayons X ou de rayons gamma comportant:

- une source d'électrons (10) configurée pour générer en fonctionnement un train de paquets d'électrons espacés (118);
- un accélérateur linéaire RF (12) adapté pour accélérer lesdits paquets d'électrons (118), qui sont dirigés le long d'un chemin dans une région d'interaction laser-faisceau d'électrons; et
- un système laser (30) adapté pour produire une impulsion laser (110), le système laser étant agencé de telle manière que l'impulsion laser est réfléchie vers ledit chemin des paquets d'électrons arrivants pour interagir avec les paquets d'électrons, de sorte que la région d'interaction laser-faisceau d'électrons s'étend le long dudit chemin,

caractérisée en ce que:

le temps de transit de chacun des paquets d'électrons accélérés dans la région d'interaction laser-faisceau d'électrons est à la fois supérieur à la durée du paquet d'électrons accéléré et supérieur à l'espacement entre les paquets d'électrons;
le système laser est adapté pour produire une impulsion laser ayant une durée au moins aussi longue qu'un temps de transit de l'impulsion laser dans la région d'interaction laser-faisceau d'électrons,
dans laquelle la durée de l'impulsion laser est:

soit égale à la longueur totale du train de paquets d'électrons espacés, de sorte qu'un seul passage de l'impulsion laser

dans la région d'interaction laser-faisceau d'électrons interagit avec tous les paquets d'électrons accélérés du train;
soit un sous-multiple entier de la longueur du train des paquets d'électrons espacés, et le système laser est agencé pour faire recirculer l'impulsion laser dans la région d'interaction laser-faisceau d'électrons pour un nombre de passages prédéterminé égal à un inverse du sous-multiple;

et produit de ce fait des faisceaux à haut flux de rayons X ou de rayons gamma quasi-monoénergétiques clairs, accordables et polarisés par diffusion Compton laser.

2. Source de rayons X ou de rayons gamma selon la revendication 1, dans laquelle la fréquence d'espacement des paquets d'électrons (118) est la même que ou est corrélée à la fréquence RF de l'accélérateur linéaire RF, de sorte qu'un paquet d'électrons est présent pour chaque cycle de ladite fréquence RF.

3. Source de rayons X ou de rayons gamma selon la revendication 1, dans laquelle ledit accélérateur linéaire RF (12) est exploité dans la bande X.

4. Source de rayons X ou de rayons gamma selon la revendication 1, dans laquelle ledit accélérateur (12) est exploité de façon nominale à 12 GHz environ.

5. Source de rayons X ou de rayons gamma selon la revendication 1, dans laquelle ledit accélérateur (12) est exploité de façon nominale à 11,424 GHz environ.

6. Source de rayons X ou de rayons gamma selon la revendication 1, dans laquelle lesdits rayons gamma comprennent une largeur de bande fractionnelle de 10E-3 ou moins.

7. Source de rayons X ou de rayons gamma selon la revendication 1, dans laquelle ladite source d'électrons comprend un photocanon.

8. Source de rayons X ou de rayons gamma selon la revendication 7, dans laquelle ledit photocanon est piloté par un laser qui fonctionne à la fréquence RF de l'accélérateur linéaire RF.

9. Procédé de production de faisceaux à haut flux de rayons X ou de rayons gamma quasi-monoénergétiques clairs, accordables et polarisés par diffusion Compton laser, au moyen d'une source d'électrons (10), d'un accélérateur linéaire RF (12) et d'un système laser (30), le procédé étant **caractérisé par** les étapes suivantes:

- générer, avec la source d'électrons, un train de paquets d'électrons espacés (118);
- accélérer, avec l'accélérateur RF (12), lesdits paquets d'électrons, qui sont dirigés le long d'un chemin dans une région d'interaction laser-faisceau d'électrons; et
- produire, avec le système laser (30), une impulsion laser (110), le système laser étant agencé de telle manière que l'impulsion laser est réfléchie vers ledit chemin des paquets d'électrons arrivants pour interagir avec les paquets d'électrons, de sorte que la région d'interaction laser-faisceau d'électrons s'étend le long dudit chemin,

caractérisé en ce que:

le temps de transit de chacun des paquets d'électrons accélérés dans la région d'interaction laser-faisceau d'électrons est à la fois supérieur à la durée du paquet d'électrons accéléré et supérieur à l'espacement entre les paquets d'électrons;
le système laser est adapté pour produire une impulsion laser ayant une durée au moins aussi longue qu'un temps de transit de l'impulsion laser dans la région d'interaction laser-faisceau d'électrons,
dans lequel la durée de l'impulsion laser est:

soit égale à la longueur totale du train de paquets d'électrons espacés, de sorte qu'un seul passage de l'impulsion laser dans la région d'interaction laser-faisceau d'électrons interagit avec tous les paquets d'électrons accélérés du train;
soit un sous-multiple entier de la longueur du train des paquets d'électrons espacés, et le système laser est agencé pour faire recirculer l'impulsion laser dans la région d'interaction laser-faisceau d'électrons pour un nombre de passages prédéterminé égal à un inverse du sous-multiple;

et produit de ce fait des faisceaux à haut flux de rayons X ou de rayons gamma quasi-monoénergétiques clairs, accordables et polarisés par diffusion Compton laser.

10. Procédé selon la revendication 9, dans lequel la fréquence d'espacement des paquets d'électrons (118) est la même que ou est corrélée à la fréquence RF de l'accélérateur linéaire RF, de sorte qu'un paquet d'électrons est présent pour chaque cycle de ladite fréquence RF.

11. Procédé selon la revendication 9, dans lequel ledit accélérateur linéaire RF (12) est exploité dans la bande X.

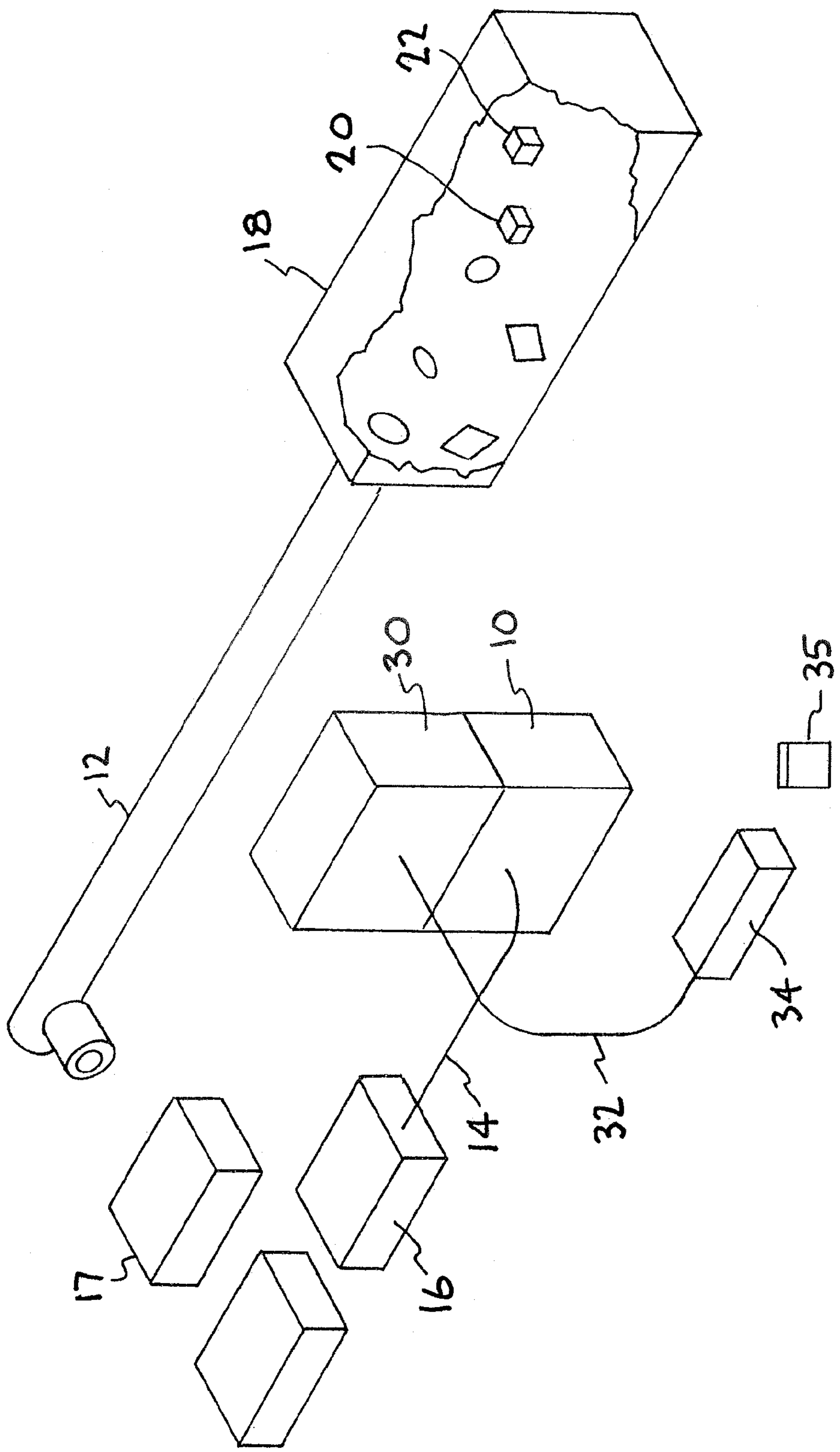

FIG. 1

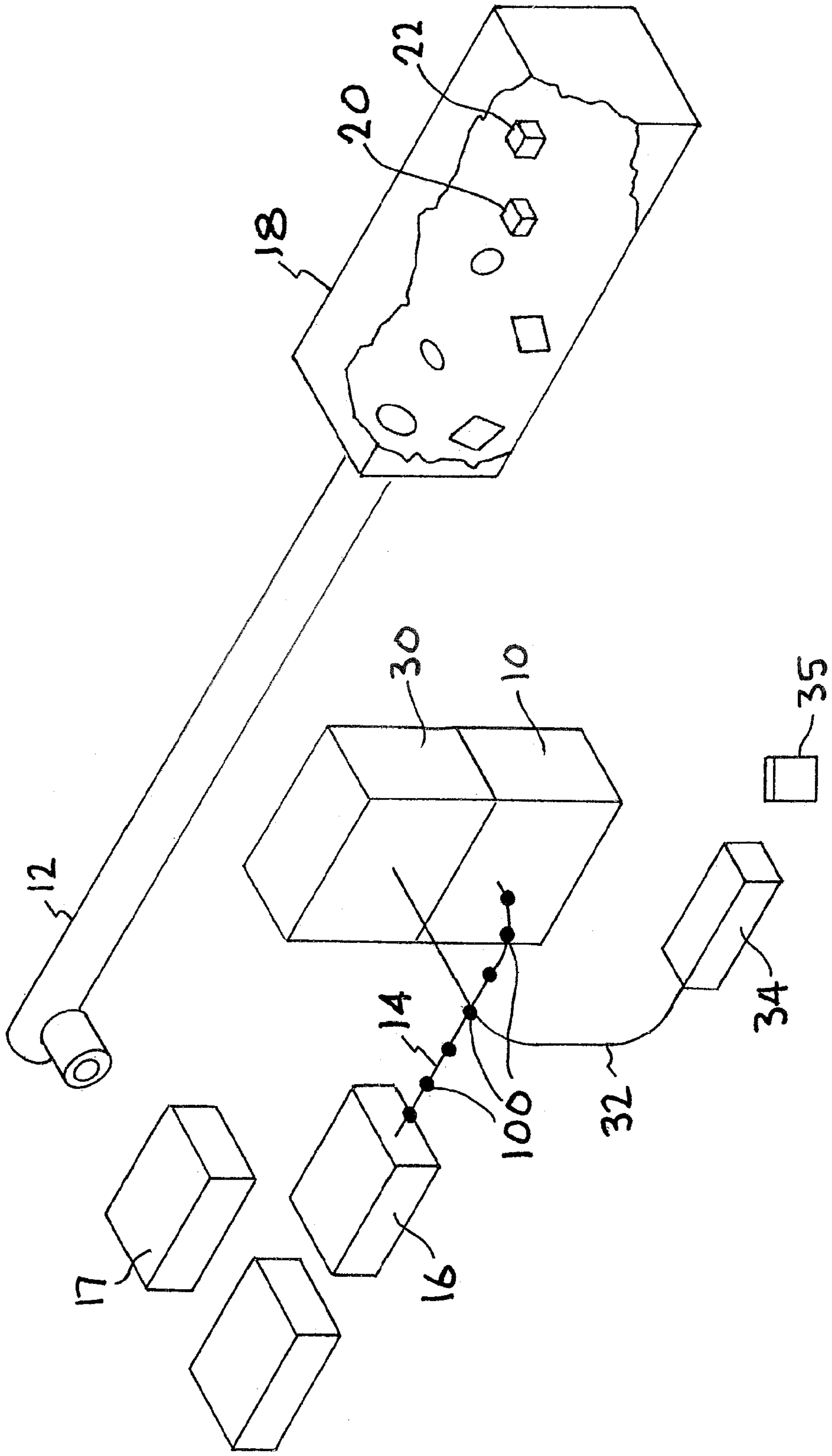

FIG. 2

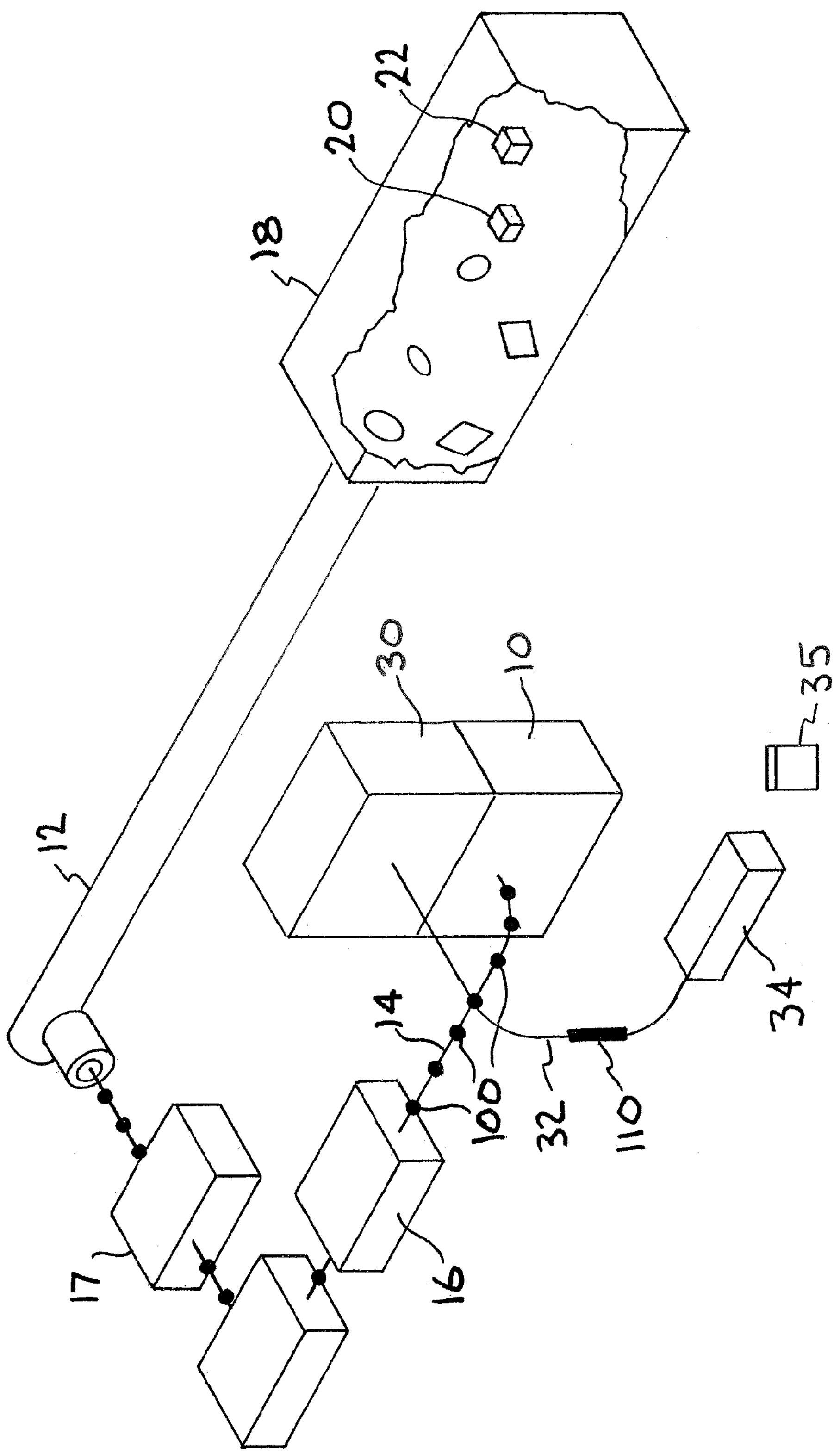

FIG. 3

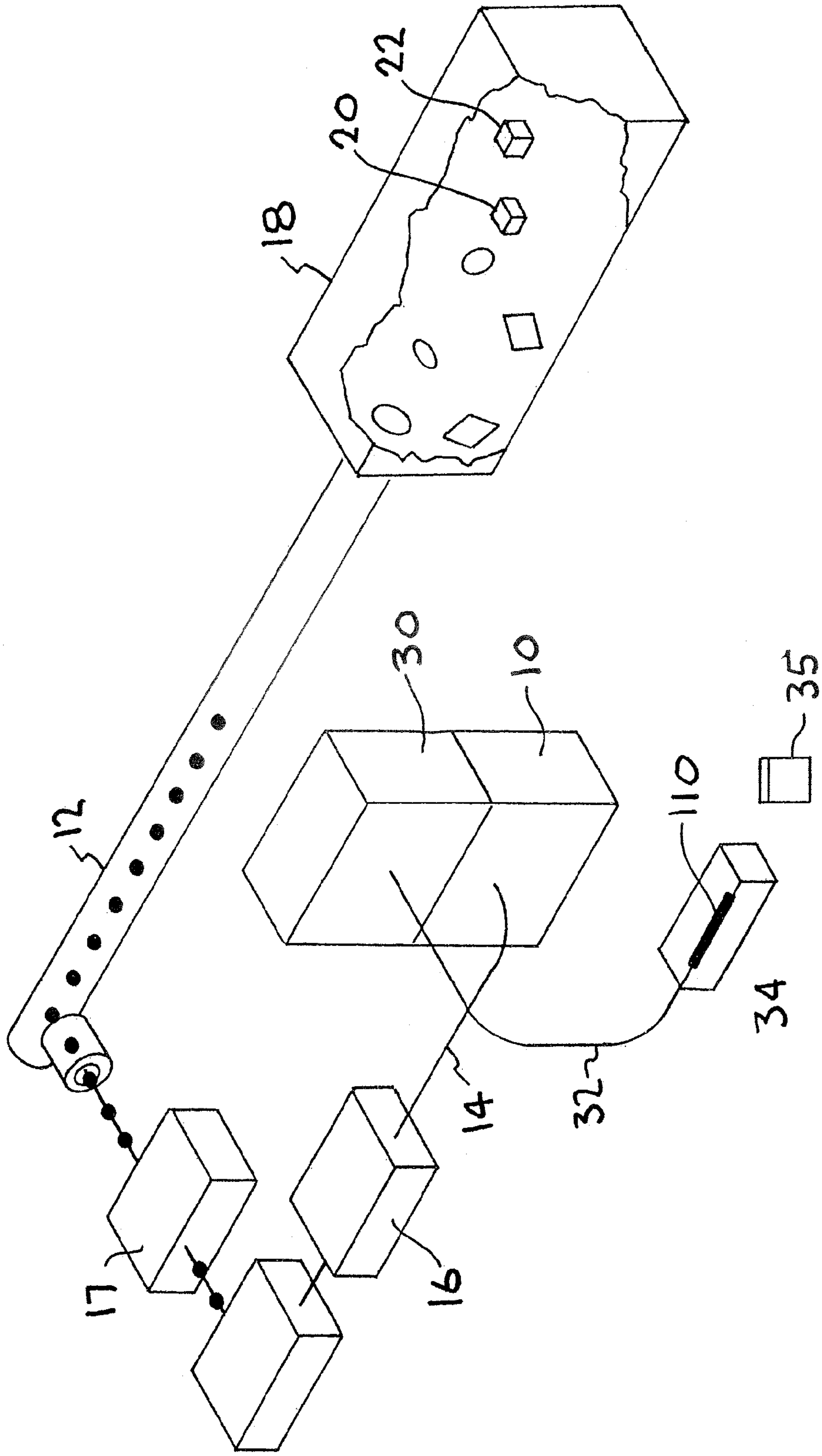

FIG. 4

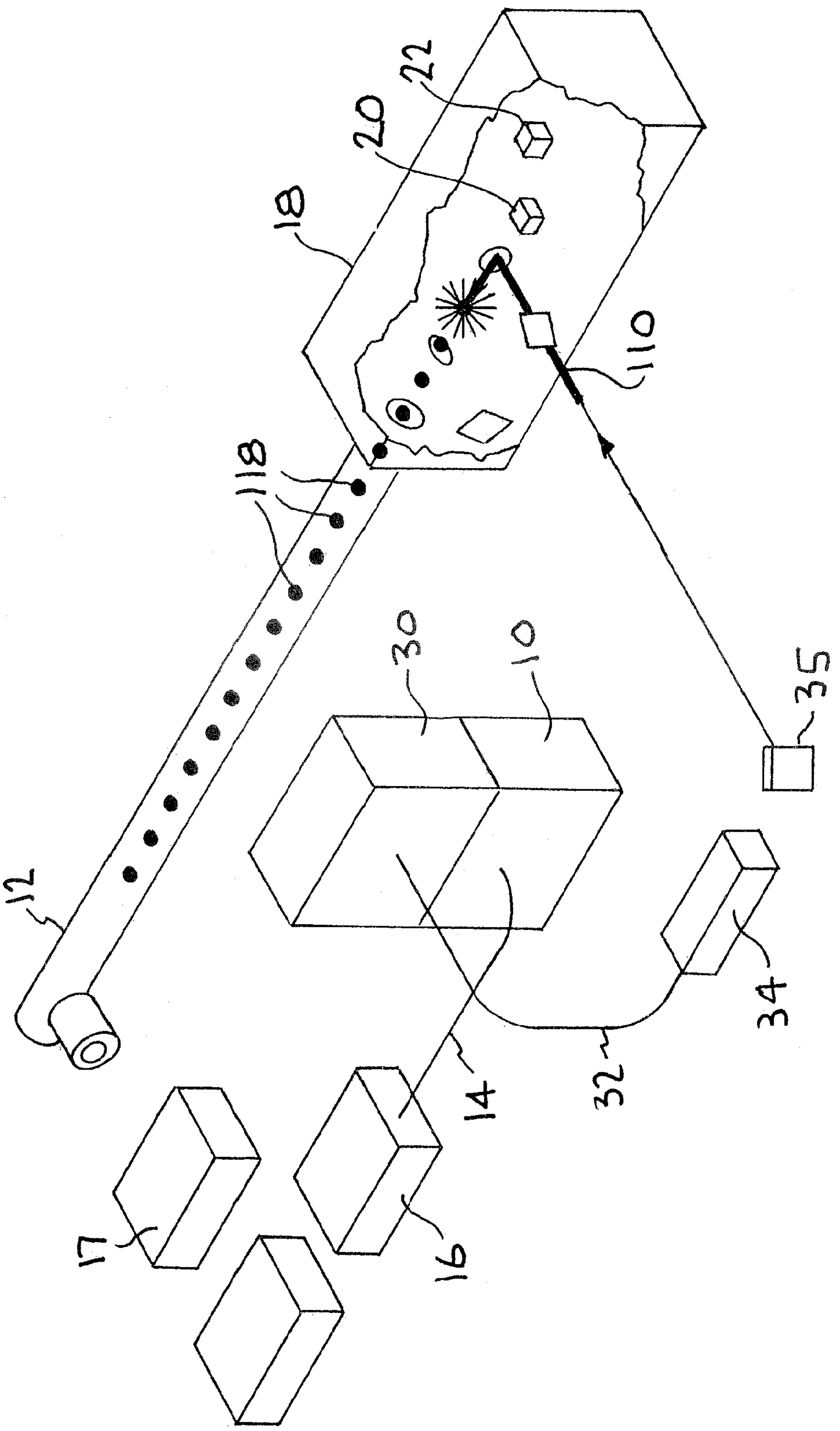

FIG. 5

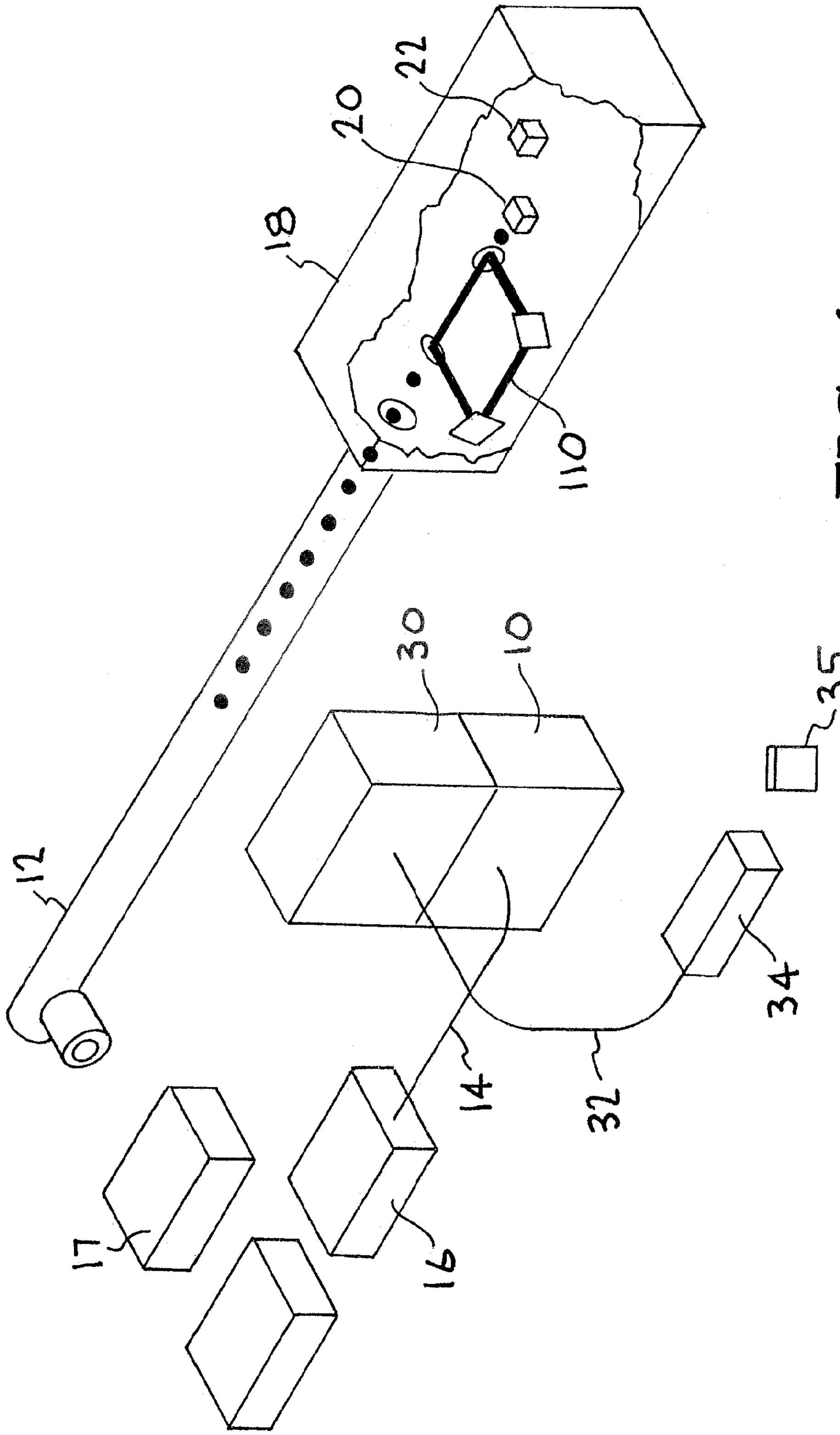

FIG. 6

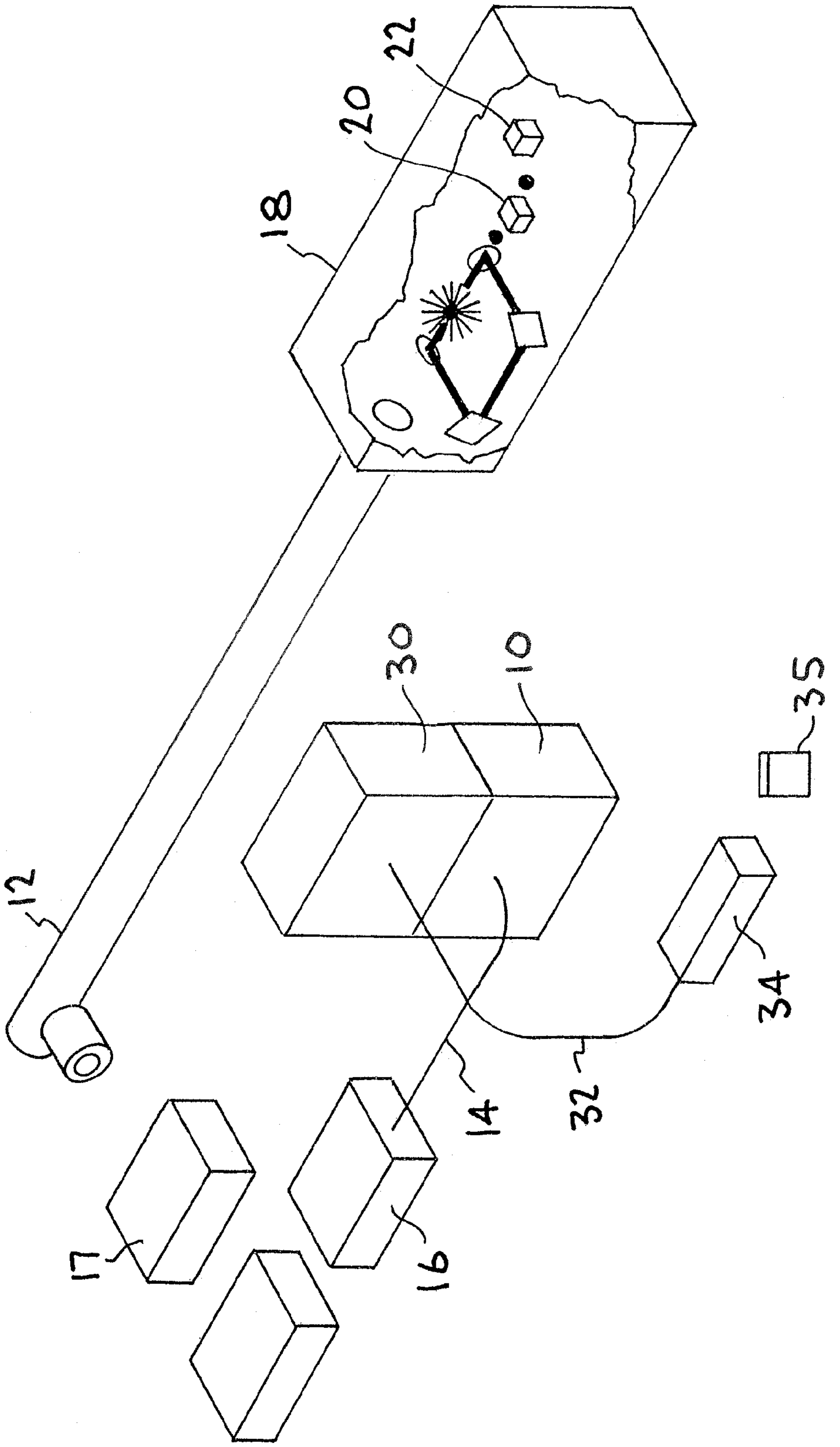

FIG. 7

REFERENCES CITED IN THE DESCRIPTION

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- DE C5207NA27344 A **[0001]**
- US 6332017 B1 **[0007]**

Non-patent literature cited in the description

- X-ray generation from slanting laser-Compton scattering for future energy-tunable Shanghai Laser Electron Gamma Source. **LUO W. et al.** APPLIED PHYSICS B; LASERS AND OPTICS. SPRINGER **[0006]**