Table-top radiation sources

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Development of low cost, high intensity radiation sources, compact enough to be mounted on an optical table, – and hence referred to as table-top radiation sources, – has been an important activity over a couple of decades. Ever since the discovery of the lasing phenomenon, increasingly powerful optical radiation sources (the word 'laser' generally refers to this category) have been realized and have been used in a variety of experimental programmes including spectroscopy and studies in atomic physics. During the past decade, several table-top lasers have been built. They, in turn, have been used to configure table-top sources of other kinds and many more may be realized in the near future. X-ray lasers, γ-ray-, neutron-, charged particle – and isotope – sources are all covered by this effort.

Basically using high power table-top lasers, generation of other radiations has resulted in promise of a spurt of activity in plasma studies, materials characterization, medical diagnostics, nuclear physics studies, isotope production, isotope separation, etc. As and when higher power lasers [of petawatt (10^{15} watts) power] get reduced in size and complexity, the consequent future developments look very promising and may be full of surprises. This article gives a brief outline of some of these developments.

Table-top lasers of terawatt power

Table-top high power and high intensity terawatt (10^{12} watts) lasers provide light energy in nanosecond (10^{-9} s) or picosecond (10^{-12} s) pulses. Until 1993, producing terawatts of power in wavelength range less than 100 nanometers required a large serpentine system occupying large laboratory space; a laser beam was split into several branches which were amplified in parallel (so as not to damage the laser rods) and then recombined at a target for any application. The concept of Chirped Pulse Amplification (CPA) has been employed since 1993 in which the beam pulse was stretched by using diffraction gratings, followed by amplification, and then the pulse was compressed[1] as shown schematically in Figure 1. This approach reduced the size and cost of high-power laser systems and provided a means of having terawatt table-top lasers[2]. Irradiance greater than 10^{18} W/cm^2 could be achieved. The CPA technique enabled existing lasers to be boosted to high power operation. For example, the VULCAN laser at Britain's Rutherford Appleton Laboratory was boosted to operate at power levels of several tens of terawatts. The high electric fields in such light beams sent through non-linear crystals produce higher harmonic waves, including X-rays. It became possible to use such high fields to accelerate electron and other charged particle beams to higher energies.

Table-top X-ray lasers for materials science and medical diagnostics

While harmonic up-conversion of high power optical lasers, synchrotron sources and free electron lasers (FEL) have been useful in generation of X-rays, the latter two, namely, the synchrotrons and FELs are large and expensive facilities. Hence is the importance of table-top X-ray systems.

Physicists have been proposing laser principle to be useful for generating X-ray beams. In X-ray lasers, when a pulse of light strikes the target, the light pulse strips electrons off the atoms of the target and the ions in the resulting plasma are excited to higher energy states. As each excited ion decays from the higher energy state, it emits a photon. If such photons all at the same wavelength, are amplified in step as in a laser, the X-ray laser beam is generated.

The first X-ray lasers were demonstrated by Matthews and co-workers[3] at the Lawrence Livermore National Laboratory and by Suckewer and co-workers[4] at Princeton Plasma Physica Laboratory, both in 1984. Since then, Nova, Livermore's largest and the most powerful laser has been used for X-ray laser research. Nova uses a very-high-energy pulse of light, about a nanosecond long, to cause lasing at X-ray frequencies. Because these high-energy pulses heat the system's glass amplifiers, Nova had to be cooled between shots; Nova could be fired only about six times a day to generate X-ray beams.

No doubt much progress has been made in the development of X-ray lasers utilizing such large laser facilities, but their large size, low efficiency and high cost have limited their widespread use. To circumvent these limitations, Rocca and his co-workers[5] at Colorado State University explored amplification schemes that use smaller laser drivers and this led to significant advance. The first demonstration of a discharge pumped soft X-ray laser driven by a simple electrical discharge was realized (by using a compact table-top discharge) that had the potential of being developed into an efficient, high-repetition-rate, cost-effective source for applications. The lasing occurred[5] in capillary cavities of length less than 15 cm and of diameter 4 mm.

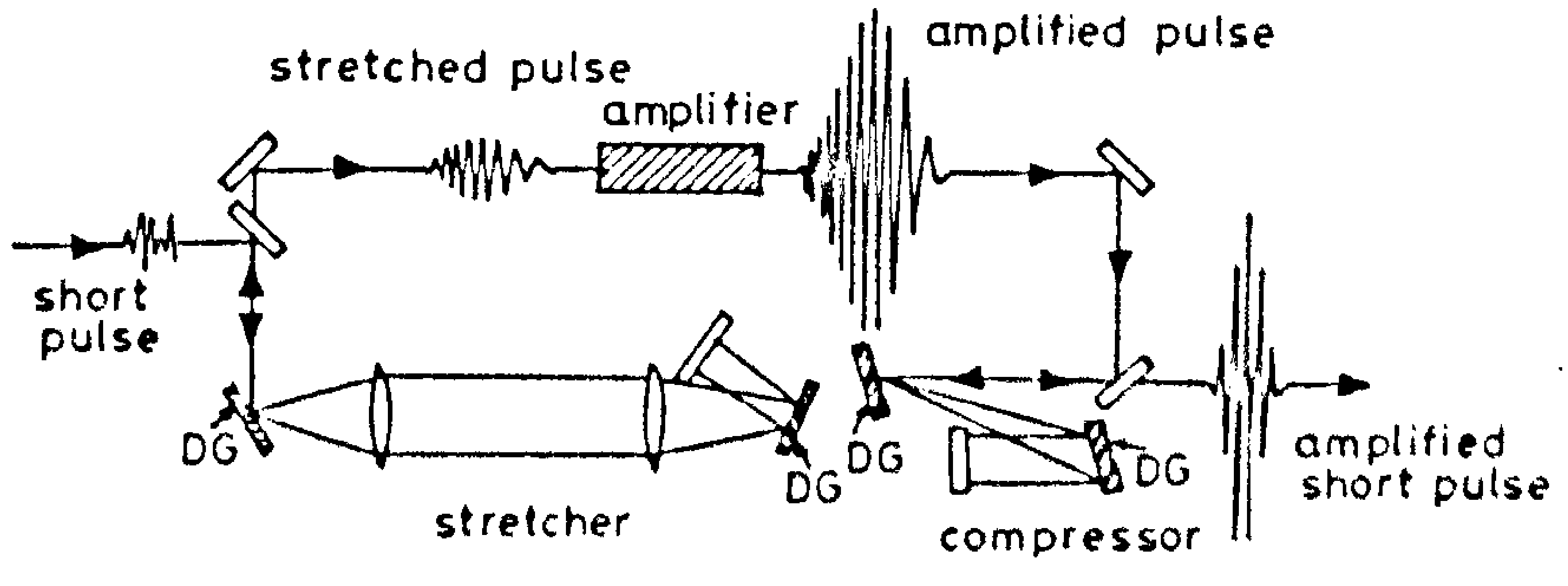

Figure 1. Schematic layout for chirped pulse amplification; DG, Diffraction Grating (from ref. 7).

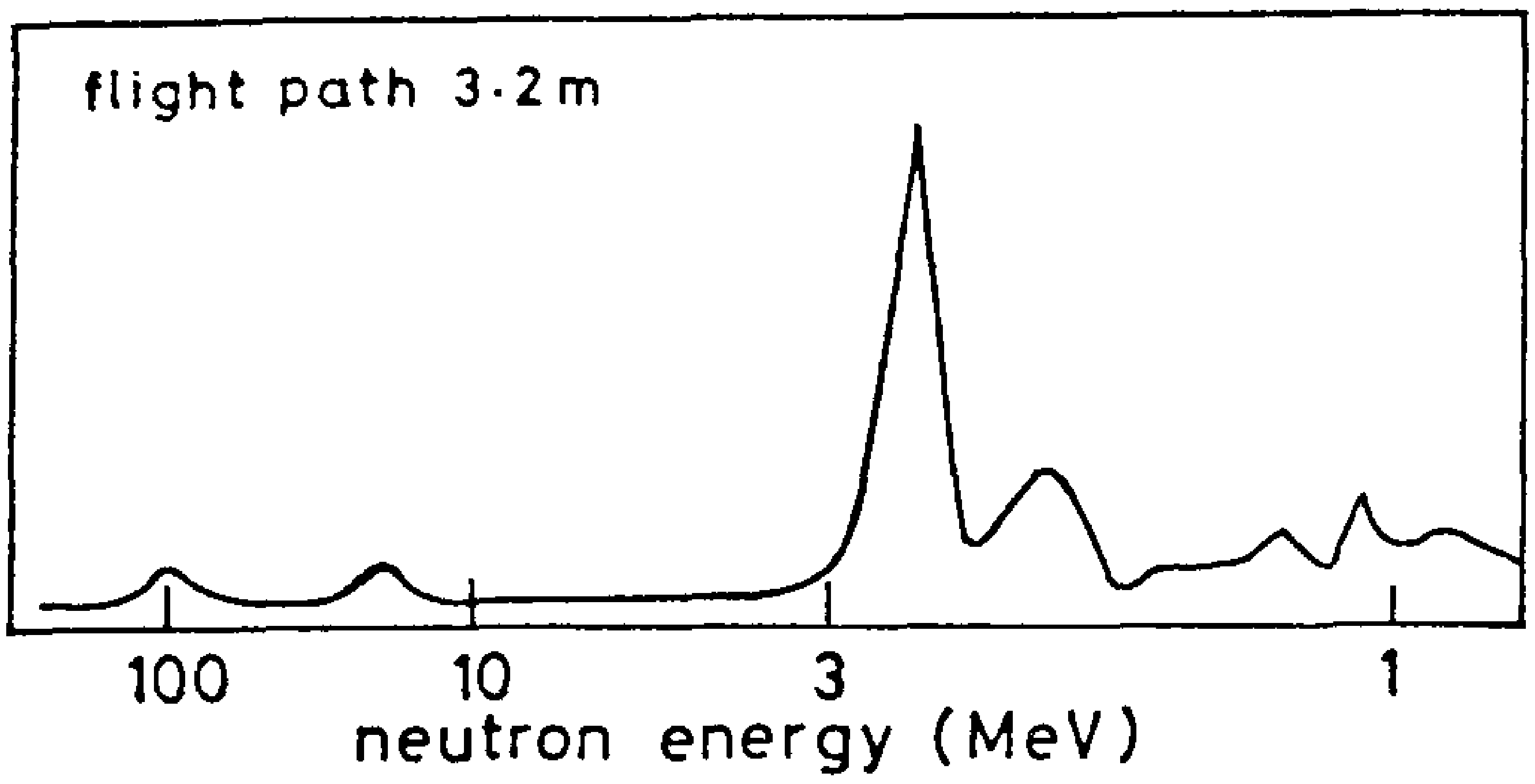

Figure 2. Time-of-flight neutron spectrum corresponding to a flight path length of 3.2 m. The peak of the spectrum corresponds to 2.45 MeV (based on ref. 8).

Using this so-called capillary discharge technique, lasing was demonstrated at a wavelength of 46.9 nm in neon-like argon. A very fast discharge pumped the argon gas, injected at nearly 700 milltorrs into the capillary, to an excited neon-like Ar^{8+} state and a hot, dense and uniform plasma was produced that lased. (The electrical discharge produced a current of nearly 40 kA for about 60 nsec.) That it was lasing was confirmed by the facts that, as the length of the capillary was varied from 3 cm to near 15 cm, intensity of the Ne-like line increased exponentially and angular spread of the line decreased. So, this demonstrated a method for development of a simple and compact laser that could lase in the soft X-ray region; the gaseous target excited by capillary discharges resulted in soft X-ray amplification. To push the wavelength to shorter wavelength region, lasing in materials produced from solid targets was important. It was realized theoretically that laser beams amplified with ions would have much higher energies than beams amplified using gases. Excitation of sulphur plasmas by a capillary discharge resulted in amplification of the $J = 0 \rightarrow 1$ line of Ne-like sulphur at 60.8 nm; the discharge excitation technique had the potential of producing amplification in the XUV region also.

Recently, a team at Livermore developed a different technique by which a small 'table-top' X-ray laser can be fired every three or four minutes. By using two pulses – one of about a nanosecond and another in the picosecond range – their laser uses far less energy and does not require the cooling-off period that lasers of Nova-type need. Scientsts had theorized for years that an X-ray laser beam could be created using an extremely short, picosecond pulse, which would require less energy. If chirped-pulse amplification is combined with lower energies, the pulses do not overheat the glass amplifiers and the system could operated frequently.

Dunn *et al.*[6] have studied palladium targets. When palladium atoms are stripped off 18 electrons, their ions become like a nickel atom, which is a closed-shell and stable configuration. If the target is made of titanium, with 22 electrons in its atoms, the ionization process strips off 12 electrons, leaving only 10 electrons in the atom, which makes the ions like a neon atom in electron configuration. Neon-like-ions in a plasma are very stable, closed-shell ions. The table-top X-ray laser used the compact multipulse terawatt (COMET) laser driver to produce two pulses. First, a low-energy, nanosecond pulse of only 5 joules strikes a polished palladium or titanium target to produce the plasma and ionise it. Then a 5-joule, picosecond pulse, created by chirped-pulse amplification, arrives at the target a fraction of a second later to excite the ions. The first transient-gain, nickel-like, X-ray lasing at 14.7 nanometers has been produced with a laser pump of less than 10 joules.

Soft X-rays are ideal for probing and imaging high-energy-density ionised plasmas. Basic research using X-ray lasers as a diagnostic tool can fine-tune the equations of state of a variety of materials, including those used in nuclear weapons. These lasers also have applications for the materials science community, to derive the crystal structure of new and existing materials. Soft X-ray sources are expected to open unprecedented possibilities in several other fields of science, engineering, and technology, including biology (X-ray microscopy and holography of living cells, etc.). For the latest in the field of X-ray lasers, one can see the review article by Rocca[7]. Table-top X-ray lasers have the advantage of high energy/pulse and potentially they are capable of producing X-ray beams of very high average power.

Table-top fission and fusion neutron sources

Writing in *Nature*, Ditmire and colleagues[8] from the Livermore Laboratory describe how they used compact but powerful lasers to excite thermonuclear fusion in a jet of deuterium gas cooled to minus 170°C. They used a table-top laser producing 120 mJ of laser energy in pulses with 35-fs pulse width at 820 nm operating at 10 Hz. As the deuterium gas expands when it is cooled, clustering of D_2 molecules to sizes of order of 50 Å takes place, each cluster containing several hundred to several thousand atoms. The laser pulse breaks up the clusters and deuterium atoms fly apart with large kinetic energy. When such high energy deuterium ions collide with each other, and if their kinetic energy is larger than a few keV, nuclear fusion between the deuteriums takes place via the D (D, ^{3}He)*n* reaction, the fusion reaction. The density of deuterium gas and the laser energy resulted in average deuterium ion energy to be at least 2.5 keV but the energy spectrum of ions contained ions of multi-keV energy also in the hot tail of the spectrum. These high energy deuteriums took part in the fusion reaction. Time-of-flight (T-O-F) distribution of neutrons produced in the (D, D) reaction, detected by means of neutron-sensitive scintillators, revealed a distinct peak in the T-O-F spectrum corresponding to the expected 2.45 MeV neutrons (see Figure 2). A respectable yield of fusion neutrons (~10^5 neutrons per joule of incident laser energy) comparable to those produced in large-scale laser fusion experiments, in the context of inertial confinement fusion research was achieved.

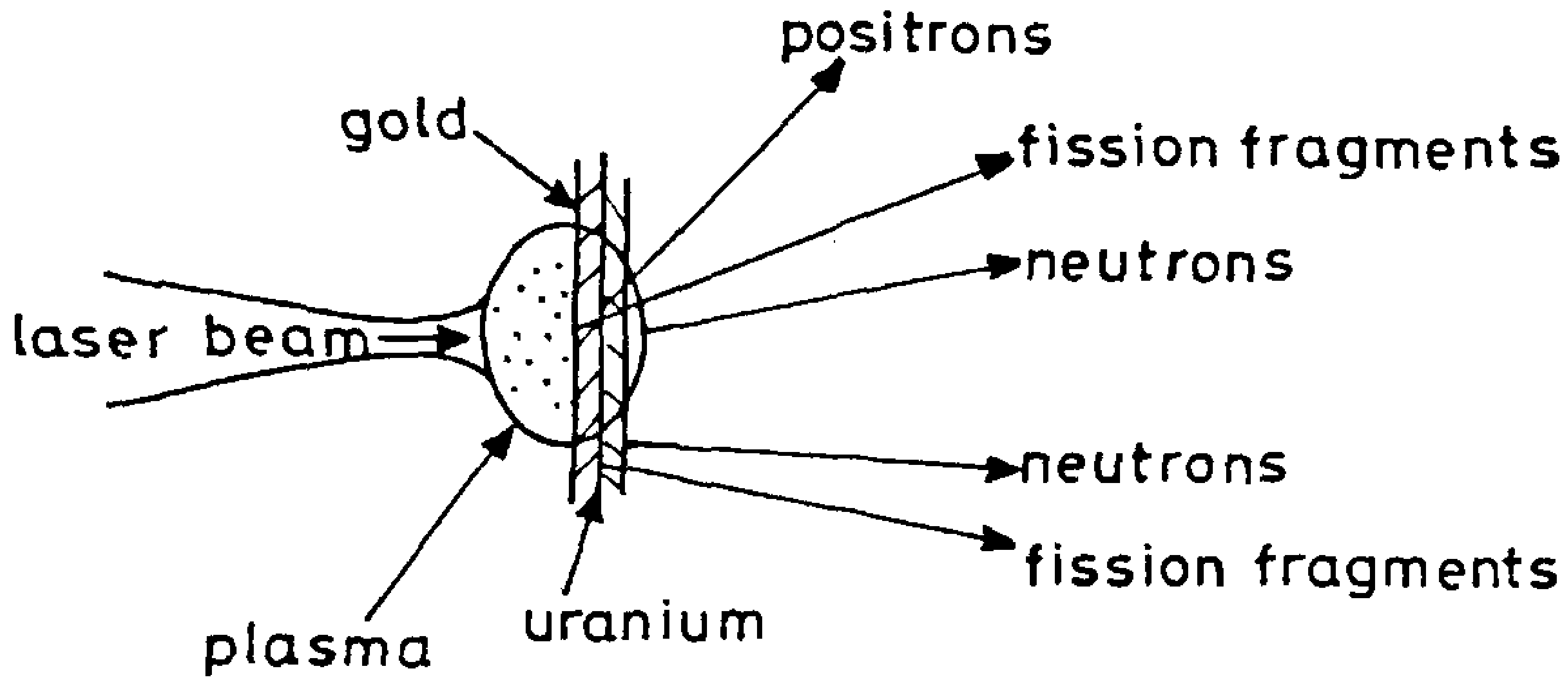

Figure 3. Schematic experimental layout in which laser-induced fission is observed as referred to in ref. 9.

Each laser pulse resulted in about 10,000 neutrons. According to Ditmire *et al.*[8], 'It may be possible in the future, to enhance the neutron yield further, perhaps by increasing the ion energies produced from exploding clusters, for example, with multiple femtosec pulses or by using two excitation wavelengths.... Such options could open the way to the production of compact, flexible, high-flux neutron sources for a vast array of uses, with applications in material science and neutron radiography for example'.

Because the fusion reaction is not self-sustaining the technique is not useful for commercial energy production. But the experiment is remarkable given the modest power of the laser and the experiment's simple set-up. The table top apparatus cost about $1 million, a fraction of the cost of the large laser facility at Livermore that is being used for inertial confinement fusion research. Using such cost-effective table-top neutron sources, more researchers may be in a position to conduct fundamental fusion research at many other laboratories that could eventually help make large fusion reactors a reality.

Table-top γ-ray sources (?) and nuclear reactions

Higher and higher power (petawatt) laser sources are used to bombard solid targets by light pulses of duration of about 1 psec. The energy transfer of near about 10^{20} W/cm^2 creates plasma and the plasma electrons get accelerated to tens of MeV. At these relativistic energies of electrons, γ-rays are produced due to Bremsstrahlung process. These γ-rays in turn knock-off high energy neutrons from the nuclei of any solid target by the (γ, n) process. These reactions are referred to as photonuclear or photoneutron reactions. That such reactions should be observable had been foretold theoretically some ten years ago. In two letters which appeared in *Physical Review Letters* on 31 January 2000, two groups have reported these photonuclear reactions.

Cowan *et al.*[9] of the Livermore group used a petawatt laser to bombard a solid gold target mounted on a copper sample holder containing uranium (see Figure 3). A lower energy laser on the target surface had created a plasma before the high energy laser pulse hit the target. As already stated, the Bremsstrahlung γ-rays knocked off neutrons from Cu and Au, which in turn led to fast fission in ^{238}U, and creation of isotopes.

Leddington *et al.*[10] of the Rutherford Appleton Laboratory used the VULCAN laser (50 terawatt power) to bombard a tantalum target with light pulse of intensity 10^{19} W/cm^2 and 1 psec duration when 50 J of energy was transferred to the target. The γ-ray beam generated, is said to be highly directional and could be used to carry out photonuclear reactions. Isotopes of ^{11}C, ^{38}K, ^{62,64}Cu, ^{63}Zn, ^{106}Ag, ^{140}Pr and ^{180}Ta were produced by the (γ, n) reaction. Nuclear fission of ^{238}U has also been demonstrated.

The photonuclear reactions have demonstrated feasibility of carrying out interesting nuclear physics experiments using laser beams, which may mean that this route will circumvent use of accelerators. Secondly, neutrons from the photonuclear reactions have been used in causing fission of ^{238}U and releasing neutrons in turn. Thirdly, a variety of isotopes have been produced via the (γ, n) reaction. If petawatt lasers could be configured in a table-top laser assembly, in future, nuclear physics could be carried out far away from expensive particle accelerators.

Table-top charged particle accelerators

As already stated, peak powers well above multiple terawatts have been demonstrated and routinely used in the terawatt solid state lasers, based on the CPA technique. Current research is focused on further increase of peak power (multiple Joules of energy in sub 100 fsec pulse length) as well as increasing the repetition rate beyond 1 Hz to a kHz and beyond.

These intense lasers are well-known to have high electric and magnetic fields. Investigations are under way to explore possibilities to exploit such intrinsic ultrahigh electromagnetic fields by coupling these lasers appropriately to a particle beam for net longitudinal acceleration and for other beam manipulations. The petawatt Livermore laser has been used for generating 30×10^{12} protons of energy up to 50 MeV by pulsing the light beam on a solid target of *nearly* 400 *microns in* size. This is reported in the November 1999 meeting of the Plasma Division of the American Physical Society. In the same meeting the University of Michigan researchers reported production of 10^9 protons of energy up to about 10 MeV using a table-top terawatt laser. So also, the scientists of the Rutherford Appleton Laboratory used the VULCAN laser to produce protons up to 17 MeV and more interestingly lead ions with energy 420 MeV. It is believed that as the laser beam hits the target, a cloud of electron plasma is generated at the back of the target, which extracts protons or ions of the solid and shoots them along the direction of the laser beam accelerating the charged particles in the process.

Table-top isotope separator

A terawatt laser has been used by Pronko *et al.*[11] at the Michigan University for isotope separation. Boron nitride and gallium nitride targets were subjected to laser pulses of 150–200 fsec (10^{-15} s) at 780 nm wavelength.

Efficient isotope enrichment process was observed directly in laser-ablation plumes generated from the ultrafast laser pulses focused on a target surface. Isotope ratios for B and Ga were observed in a time-of-flight electrostatic analyser. Enrichment factors of 2 or more above natural abundance were observed for the ratios of ^{10}B/^{11}B as well as for ^{69}Ga/^{71}Ga. These same plumes were also used to deposit isotopically pure enriched films of boron nitride on silicon. The intense magnetic fields associated with light pulses helped in depositing the isotopes at different locations on the silicon disk depending on the weight of the isotopes.

Summary

The current status of table-top X-ray lasers is that laser-pumped soft X-ray lasers operating at wavelengths of the order of 15 nm have been possible using several joules of excitation energy under saturation condition; soft X-ray amplification has been seen even with fractions of a joule of laser excitation energy. According to Rocca[7], 'a very compact 26.5 eV discharge pumped laser operating at several Hz, producing millijoule level laser pulses and average power of 3.5 mW is comparable to that generated by a third generation synchrotron beam line when one realizes that it produces a spatially coherent laser average power per unit bandwidth of similar magnitude'.

These compact experimental set-ups mean that many researchers will have access to sources of X-rays or neutrons for all kinds of research applications in their own research institutes, without having to use the giant-sized facilities, found only in the very large national laboratories.

So what are the developments that have helped in ushering in this era of radiation sources which one could not have dreamt of, say, two decades ago. There are a few important leading ones according to Rocca[7]. They are: (a) developments of multiwatt table-top optical laser systems based on chirped pulse amplification; (b) fast capillary discharges which helped in creating plasma columns with very high uniformity and length to diameter ratio; (c) achievement of very important reduction in the laser pump energy required for lasing to less than 1 J; (d) soft X-ray optics, etc.

In conclusion, it may be stated that with the realization of small compact radiation sources, a variety of applications in diverse fields, from nonlinear optics to medical diagnostics are foreseen. But more importantly, as Rocca has said, 'several of the most important applications may yet have to be proven. When novel practical sources of intense electromagnetic field were developed in the past, new regimes of physical parameters became accessible, often resulting in the observation of unexpected phenomenon that led to important scientific and technological breakthroughs'.

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