Laser-Generated Intense Planck Radiation

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The physics of radiation in thermal equilibrium with matter has been well known since Max Planck’s discovery of the so-called law of black-body or, as we shall call it, Planck radiation at the beginning of this century. Until recently, it has not been possible to generate Planck radiation with temperatures exceeding $10^4 - 10^5$ K in the laboratory, because of the strong increase in the radiant energy flux with temperature. From the Stefan-Boltzmann law one finds a flux of $6 \times 10^{12}$ W/cm$^2$ for a temperature of $10^6$ K, increasing with the fourth power of the temperature. The losses which arise when such enormous fluxes of radiation circulate are so high that the radiation field cannot be maintained by ordinary power sources.

The situation has changed in recent years, however, with the advent of modern pulsed power generators, such as pulsed lasers and particle beams. These sources offer the possibility of generating radiation fields with temperatures of up to about $5 \times 10^8$ K in the laboratory. This possibility is of great scientific and technical interest, e.g. for the generation of an intense soft X-ray radiation source, the laboratory study of phenomena of radiation hydrodynamics, the investigation of matter in a new range of high pressures, and the production of energy by thermonuclear fusion.

The Basic Scheme

The method of generating intense Planck radiation by a laboratory source is shown in Fig. 1. An external source delivers energy into a mm-size cavity enclosed by a solid wall. With a laser source one, or preferably several small holes in the wall are required for transmitting the beam whereas a particle beam can penetrate a wall that is thin yet still thick enough to contain the thermal radiation in the cavity. The rapid deposition of energy in the cavity is supposed to heat the inner wall to a high temperature and to generate intense Planck radiation in equilibrium with the wall. For the applications envisaged, it is important that at these elevated temperatures the radiative exchange of energy between different wall elements is so effective, that very uniform conditions are established in the cavity even if the initial wall irradiation by the source is not uniform. Furthermore, because photons propagate with the speed of light, the radiation field may be formed in the empty cavity before it fills with evaporated, hot plasma from the wall.

Crucial to the success of this concept is the confinement of the radiation by the cavity. In contrast to infrared or visible light, no reflecting walls exist for the soft X-rays that dominate the Planck distribution at the temperatures under consideration. The photon flux, incident on the wall from the interior of the cavity, is completely absorbed, and the radiation field can exist only in equilibrium with a hot layer on the inner surface of the cavity, re-emitting the incident energy. Consequently, even though the wall material forces the radiation to diffuse, thus reducing the outward energy flux and, in a sense, confining it, a fraction of the available energy is used for simply heating material. If this energy loss is too large, the desired intensity and uniformity may not be achieved.

We note that a somewhat similar situation exists in the interior of the Sun, where the peripheral layers confine the intense radiation field in its centre. Unlike the static situation in the Sun, however, we are dealing here with a problem which is extremely time-dependent.

The Confinement of Equilibrium Radiation

In order to predict the temperature in the cavity, the radiative transfer problem 1) into the wall has to be solved. The solution has not only to take into account the unavoidable expansion of the heated material (see inset of Fig. 2), but in principle also the thermalization process of the source radiation. In this general form the problem is exceedingly difficult, if not unsolvable.

In a situation where we seek to generate Planck radiation in equilibrium with the wall, it is natural to start by assuming local thermodynamic equilibrium (LTE) between radiation and matter. In the LTE approximation, the real source is replaced by an ideal source, i.e. a source of heat; its physical nature and the thermalization process can thus be ignored. If we postulate in addition that the hot, multiply ionized wall material possesses the maximum possible opacity for thermal radiation (given by a theorem of Bernstein and Dyson) we are specifying conditions which give the highest temperature we can hope to achieve in the cavity.

The major aspects of radiation confinement can be studied in a planar «cavity» consisting of two walls of infinite extent. The LTE assumption reduces the mathematical difficulties to such an extent that the scaling laws for the temperature can be obtained immediately by dimensional analysis from the governing parameters of the problem. These are found merely by inspection of the hydrodynamic equations, which include motion and radiative heat conduction, and the boundary conditions of the problem 2). The result is shown graphically in Fig. 2. The diagram is for a high-Z material (gold) for which the opacity is expected to be closest to the maximum possible.

In Fig. 2 it is assumed that the wall is continuously irradiated with a source flux $S_0$. For a short initial period, whose duration depends on $S_0$, the radiation mean free path $\lambda$ is larger than the thickness $L$ of the heated wall layer and hence radiation and matter are far out of

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Fig. 1 — Generation of intense Planck radiation in a cavity heated by a pulsed power source. An optimistic estimate of the temperature attainable with existing lasers yields $5 \times 10^8$ K, corresponding to a radiant energy flux of $\sigma T^4 = 4 \times 10^{16}$ W/cm$^2$ and a maximum of the Planck spectrum at $\sim 6$ Å.
equilibrium. However, it is expected that to the right of the border line $I_0 = I$, the LTE assumption becomes gradually valid. Figure 2 shows that the temperature rises with time. This can be understood by realizing that the radiation field in the cavity is in quasistationary balance between the gain of energy from the source and the loss of energy into the wall (transit time effects of the radiation across the cavity are negligible). Because the radiation escaping into the wall has to diffuse through an increasing mass of hot material, the loss decreases with time and the temperature can rise.

Also seen in Fig. 2 are lines of constant $N$, defined as the circulating radiant energy flux divided by the source flux, i.e. $N = \sigma T^4 / S_s$. This quantity is none other than the quality factor of the cavity for incoherent radiation. The symbol $N$ (rather than $Q$) was chosen because the quality factor is numerically equal to the number of re-emissions of the source power in the cavity before it is lost into the wall.

Figure 2 shows that $N$ becomes larger than one as the temperature rises along a line of constant $S_s$ owing to the confinement effect of the highly re-emitting walls. This phenomenon that creates the main interest in cavity heating. It means that a cavity can not only transform the source radiation into soft X-rays, but also generate an $N$-fold flux enhancement. The converted radiation that is produced can be radiated through a small hole or absorbed in a small non-re-emitting object with great efficiency.

For pulse lasers, it is perhaps most important that multiple re-emissions will smooth out unavoidable irregularities in the initial irradiation so creating uniform conditions in the cavity. This may be of great importance in certain applications as a means of overcoming the fundamental difficulty of obtaining uniform energy deposition by direct irradiation owing to the coherency of laser light.

In a real cavity the heating cannot go on for ever as suggested by Fig. 2. Hot plasma from the wall will fill the cavity and when the plasma frequency exceeds the laser frequency, the laser light can no longer penetrate. Filling can be retarded by choosing a larger cavity, but the surface area is then increased and the laser has to deliver a higher total power. The attainment of high temperatures becomes thus a matter of the power of the laser. We have estimated $n$ that in a cavity of 2 mm radius, irradiated at $10^{14}$ W/cm$^2$, heating will self-termi­nate after about 2 ns. By then a temperature of $5 \times 10^6$ K with $N \approx 30$ re-emissions would have been reached and the laser energy delivered into the cavity would have totalled $10^8$ J. Lasers designed to deliver such powerful pulses do not exist $^1$.

**Experiments with Lasers**

Cavity heating experiments have been reported by the Institute for Laser Engineering (ILE), Osaka University $^4$), and the author's institute (MPQ) $^5$). Both glass (ILE) and iodine (MPQ) pulse lasers have been used.

At MPQ, we irradiate very small cavities (0.25-1 mm diameter) in order to compensate for the limited laser energy available (≤ 100 J). The cavities are spherical and made from gold (see Fig. 3). They have an entrance hole for the laser beam and a smaller diagnostic hole which allows us to measure the radiant energy flux and the spectrum of the radiation in the cavity. Recent progress in soft X-ray instrumentation has meant that such measurements can be made with the required spectral, temporal, and spatial resolution.

The spectrum is measured absolutely for wavelengths ≥ 5-10 Å using free-standing transmission gratings, made from gold and carrying presently 1000 bars/mm. The gratings can be integrated into small pinholes for simultaneous measurement of intensity and temperature with time if a contour of constant $T^4 / S_s$ is drawn against the inner wall of the cavity. $N$ is the quality factor for radiation confinement. The diagram is for an ideal source and maximum opacity. The inset shows the density and temperature profile of the wall before and after the onset of irradiation (m is the mass coordinate).

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The temperature in the cavity can be obtained by projecting the X-ray values of the average laser flux $S_1$ absorbed on the inner wall of the cavity. Comprehensive measurements made with a soft X-ray streak camera in the most spatial resolution transverse to the dispersion direction. The detector is absolutely calibrated, gelatine-free film. Temporal resolution is achieved with a new soft X-ray streak camera. In the most comprehensive measurements made with this, temporal and spectral resolution are obtained by projecting the X-ray spectrum onto the streak slit of the camera. In this way the time-history of the temperature in the cavity can be obtained with about 20 ps resolution.

We present in Fig. 4 time-resolved spectral measurements in cavity irradiation experiments at a laser wavelength of 1.3 μm for different values of the average laser flux $S_1$ absorbed on the inner wall of the cavity. This last is derived from the measured laser energy absorbed, the area of the inner surface of the cavity and the laser pulse duration (0.3 ns). In all three cases a heating phase, determined by the rise-time of the laser pulse, and a cooling phase extending somewhat beyond the laser pulse duration may be distinguished. For the lowest flux ($2 \times 10^{12}$ W/cm$^2$) the X-ray emission occurs preferentially around 50 Å, for the intermediate flux ($7 \times 10^{12}$ W/cm$^2$) around 50 Å and 20 Å and for the highest flux ($3 \times 10^{13}$ W/cm$^2$) mostly at about 20 Å. This shift is not unexpected and corresponds to the shift in the emission of a Planck radiator with increasing temperature.

In these experiments the flux was increased by decreasing the cavity size and using a constant laser energy and pulse duration. Simultaneous measurements of the laser light reflected by the cavity showed that with the smallest cavities (250–280 μm diameter) we had reached the limit for energy acceptance set by plasma filling. For an absorbed laser energy of 20 J we measured a radiant energy flux in the cavity corresponding to a brightness temperature of $1.3 \times 10^8$ K. A considerably higher brightness temperature of $2.2 \times 10^8$ K has recently been achieved in joint experiments with ILE, using larger cavities and more energetic laser pulses.

A likely reason for the observed structures in the experimental spectra is incomplete equilibrium in the cavity — not unexpected with such low energy laser pulses and cavities consisting of a real material whose opacity is less than the theoretical maximum. To interpret the spectra, more detailed calculations which take the spectral opacity of the actual wall material into account have to be done.

For the calculations presented here it is assumed that the density and temperature profile of the hot wall material are given by the LTE solution of the radiative transfer problem, the ablative heat wave. Spectra are obtained by solving the radiation transfer equation for these profiles on the basis of spectral opacities for gold, calculated in a hydrogenic average ion model. Figure 5 shows the Planckian spectrum corresponding to the LTE prediction for the wall temperature and the calculated spectrum radiated by the hot wall material.

The calculations reproduce well the observed maxima (attributed to transitions in the N- and O-shell of multiply ionized gold) as well as their shift and relative intensity. Thus the observed spectral structures are in fact normal for this experiment. It is also seen in Fig. 5 that, as the laser flux increases, the spectra tend to fill the area under the Planck curve, indicating the trend to equilibrium. For the highest applied laser intensity the spectrally integrated flux approaches the equilibrium flux within a factor of 0.4. A better approach could be expected for more energetic laser pulses and a wall material optimized with respect to its opacity.

However, the absolute value of the radiant energy flux in the cavity is less (by a factor of 0.8 - 0.3) than predicted. Obviously the laser falls short of the ideal source assumed in the calculations, with part of the energy being lost into non-radiative channels. Evidently, the generation of higher temperatures is not merely a question of source flux and wall opacity; the physical nature of the laser source also counts. Its role is particularly difficult to analyse owing to the complexity and non-linearity of laser-plasma interaction.

**Discussion and Perspectives**

There are good prospects that the laboratory generation of intense Planck radiation could evolve rapidly. Lasers are...
by now highly developed, flexible tools, well suited to basic investigations. Continuous progress is also made in the soft X-ray instrumentation needed for diagnostics e.g. in the fabrication of gratings, precise surfaces for X-ray optics, dielectric mirrors, and detectors. Modern computers can solve the complex atomic physics problems of radiative heat transfer with adequate accuracy.

According to the present understanding of laser-plasma interaction, short-wavelength lasers seem most suitable for the generation of high-temperature radiation in a cavity.

This is not only because of their high X-ray conversion efficiency (0.8 for $\lambda_L = 0.26 \mu m^2$) but also because of the relative absence of detrimental effects like suprathermal electron generation which dominates the laser-plasma interaction completely for the long-wavelength $CO_2$ laser. Considerable efforts are presently made to generate high-power, short-wavelength laser radiation either by frequency conversion in crystals or by constructing excimer lasers. In the more distant future, pulsed heavy ion beams may become an alternative, because a favourable thermalization of the beam energy and a high efficiency of the generator are expected.

The scientific interest in the generation of intense Planck radiation has to do with the new possibilities to study the physics of emission and absorption of...
radiation at high temperatures, to perform experiments in the field of radiation hydrodynamics in the laboratory and to generate in a controlled manner very high pressures by exposing a specimen to the very uniform and intense radiation in a cavity. «Astrophysics in the laboratory» is a good characterization of the direction of this new field.

The most ambitious technical application is the production of electric power by inertial confinement fusion. The principle is to implode and ignite a fusion capsule by exposing it to the intense radiation in a cavity. A large laser built for fusion research at Osaka University is shown in Fig. 6. However, even if ignition could be demonstrated in the next decade, the need to construct power sources with adequate efficiency would probably postpone economic power production into the next century. Unfortunately the research programmes in several countries are secret being primarily directed towards more immediate potential military applications. Inertial confinement fusion is thus another example of how the results of modern science can serve or harm mankind.

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REFERENCES
3. Laser Program Annual Report 84, Lawrence Livermore National Laboratory, Report UCRL-50021-84 (June 1985), available from NTIS.