Laser-Generated Intense Planck Radiation

R. Sigel, Garching

(Max-Planck-Institut für Quantenoptik)

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 6×10^{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 5×10^6 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.

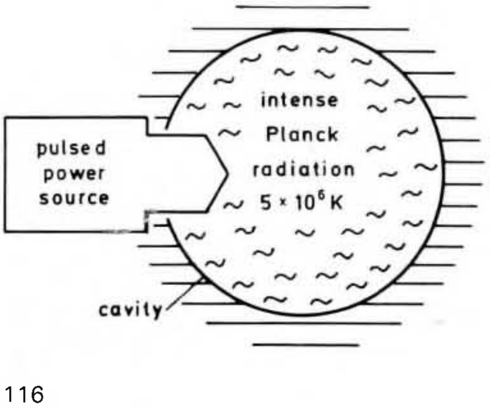

Fig. 1 — Generation of intense Planck radiation in a cavity heated by a pulsed power source. An optimistic estimate of the temperature attainable with existing lasers yields 5×10^6 K, corresponding to a radiant energy flux of $\sigma T^4 = 4 \times 10^{15}$ W/cm^2 and a maximum of the Planck spectrum at ~ 6 Å.

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_s. For a short initial period, whose duration depends on S_s, the radiation mean free path l_R is larger than the thickness l_T of the heated wall layer and hence radiation and matter are far out of

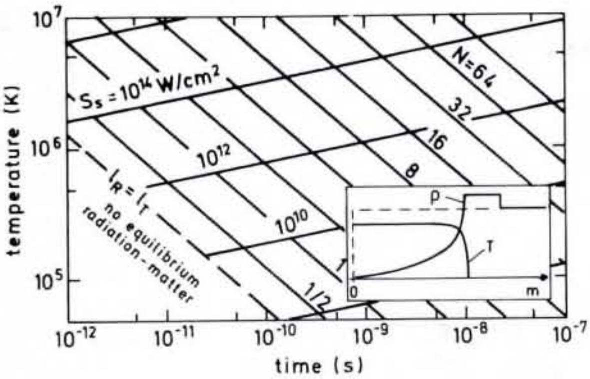

Fig 2 — Increase of the temperature with time if a constant source flux S_s is directed against the inner wall of a cavity. N is the quality factor for radiation confinement. The diagram is for an ideal source and maximum opacity. The inset shows the density and temperature profile of the wall before and after the onset of irradiation (m is the mass coordinate).

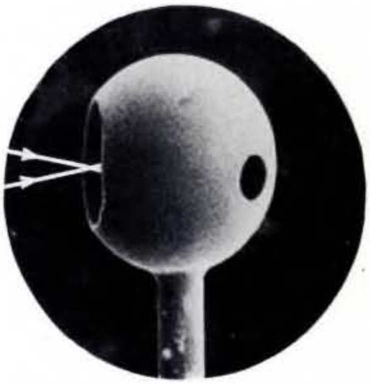

Fig. 3 — Spherical gold cavity (diameter 280 µm, wall thickness 2 µm) with an entrance hole for the laser beam and a diagnostic hole (manufactured by Fa. Dr. Johannes Heidenhain, D-8225 Traunreut).

equilibrium. However, it is expected that to the right of the border line $I_R = I_T$ 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. It is 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 [2]) that in a cavity of 2 mm radius, irradiated at 10^{14} W/cm², heating will self-terminate after about 2 ns. By then a temperature of 5×10^6 K with N ≅ 30 re-emissions would have been reached and the laser energy delivered into the cavity would have totalled 10^5 J. Lasers designed to deliver such powerful pulses do now exist [3]).

Experiments with Lasers

Cavity heating experiments have been reported by the Institute for Laser Engineering (ILE), Osaka University [4]), and the author's institution (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

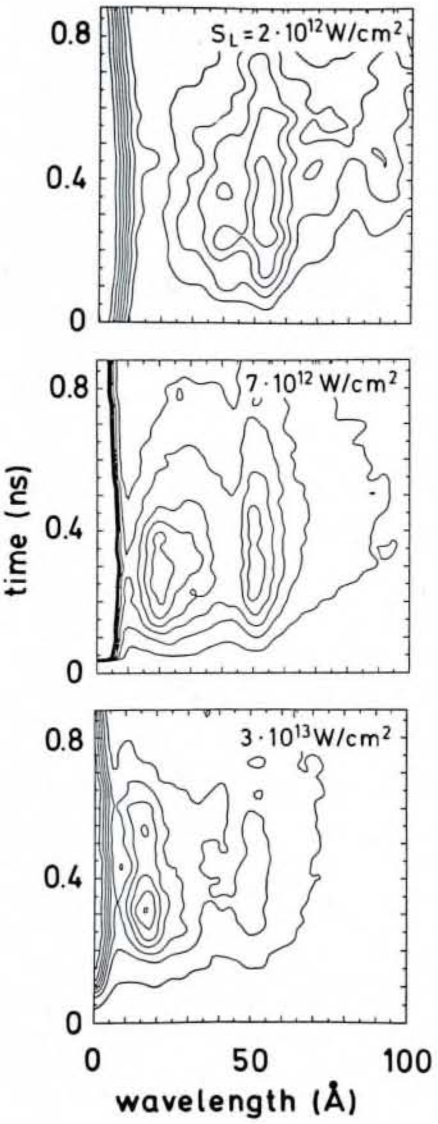

Fig. 4 — Time-resolved soft X-ray spectra (iso-intensity plots) from laser heated cavities recorded by an X-ray streak camera. Parameter is the average absorbed laser flux S_L. Along the time axis one half of the zero order is seen. Laser pulse duration was 0.3 ns.

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 [5]) made at MPQ in cavity irradiation experiments at a laser wavelength of 1.3 μm for different values of the average laser flux S_L 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 (2×10^{12} W/cm²) the X-ray emission occurs preferentially around 50Å, for the intermediate flux (7×10^{12} W/cm²) around 50 Å and 20 Å and for the highest flux (3×10^{13} W/cm²) 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 1.3×10^6 K. A considerably higher brightness temperature of 2.2×10^6 K has recently been achieved in joint experiments with ILE, using larger cavities and more energetic laser pulses [6]).

A likely reason for the observed structure 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 [2]). 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 [5]). 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

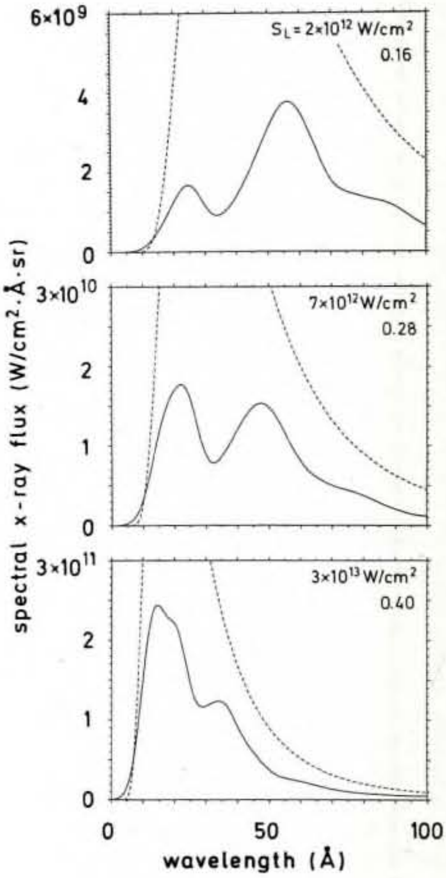

Fig. 5 — Spectra calculated for the experimental conditions of Fig. 4. With increasing laser flux S_L the spectra approach the Planckian spectra (dashed line) corresponding to the wall temperature. The number below the S_L value indicates the ratio of the area under the calculated to the area under the Planckian spectrum.

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 $\lambda_L = 0.26\ \mu m^3$) 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

Research Associateship in Experimental Nuclear Physics

There is a vacancy for an experimental physicist to join the nuclear physics group as a Research Associate at the Daresbury Laboratory, an establishment of the Science and Engineering Research Council situated in the North Cheshire countryside.

The Group is involved in a research programme on the Nuclear Structure Facility, a large tandem accelerator which currently is operating at up to 20 MV on terminal.

The principal areas of study are: direct reactions with light and heavy ions, production of exotic nuclei far from stability, nuclei with very high angular momentum, nuclear breakup and fragmentation and studies of isotope shifts and hyperfine structure using laser-induced resonance fluorescence. Experimental equipment includes advanced gamma-ray detector arrays, a Q3D magnetic spectrometer, and a 1m scattering chamber. An isotope separator operates in either on-line or off-line modes in conjunction with an associated dilution refrigerator and a beam line for laser studies. A recoil separator has recently been brought into full operation, and a heavy-ion polarized source is in an advanced commissioning stage.

Applicants should possess a PhD degree or expect to obtain one during 1986.

An appointment will be made at a salary between £9321 and £12,488 per annum depending on age, ability and experience. The post is available for a fixed term of three years and is superannuable.

CLOSING DATE: 28th November, 1986.

For further information please write or phone Dr J. Lilley on Warrington (0925) 603558.

Application forms may be obtained from and should be returned quoting reference DL/970 to: The Personnel Officer, Science and Engineering Research Council,
Daresbury Laboratory, Daresbury,
Warrington, Cheshire
WA4 4AD, England.
Tel: (0925) 603467.

Daresbury
SCIENCE & ENGINEERING
RESEARCH COUNCIL

KERNFORSCHUNGSANLAGE JÜLICH GmbH

The KFA is a large national research centre funded by the Federal Republic of Germany and the State of North Rhine-Westphalia.

We are seeking TWO DIRECTORS

jointly to lead our future **«Institute for Thin Film and Ion Technology».**

This Institute will support the research and development program of the KFA on the fundamentals of information technology by its own research contributions as well as by making available and developing a wide range of modern techniques for the deposition and characterization of thin films or film systems. By opening its facilities to universities and to industry, the Institute is also expected to become a centre for thin film preparation and analysis. A staff of 100 to 120 is envisaged for the Institute.

Topics for research and development are currently expected to include: film-systems, meeting the future requirements of information technology (multilayers of amorphous and crystalline semiconductors, magnetic and magneto-optical layers for data storage, metallization systems, layers for mechanical or chemical protection), ion and laser techniques for the manufacture, modification and analysis of films, and the development of advanced ion beam methods.

Applications for the positions are invited from scientists at universities as well as industrial and governmental laboratories. Applicants are expected to possess the capacity to lead a research establishment and to have outstanding knowledge and experience in the above fields. The candidates must be ready and willing to cooperate with industry, universities and also other institutes at the KFA.

It is planned that the directors receive tenure, as full professors at universities in North Rhine-Westphalia. The salary will conform to the C-4 scale of the German civil service. The status of a senior lecturer at a university («Habilitation») or an equivalent scientific qualification is required.

Applications accompanied by a curriculum vitae, a list of publications and a short description of previous scientific activities should be submitted by 31 October, 1986 to

KFA
Vorstand der Kernforschungsanlage Jülich GmbH
Postfach 1913, D-5170 Jülich, Federal Republic of Germany

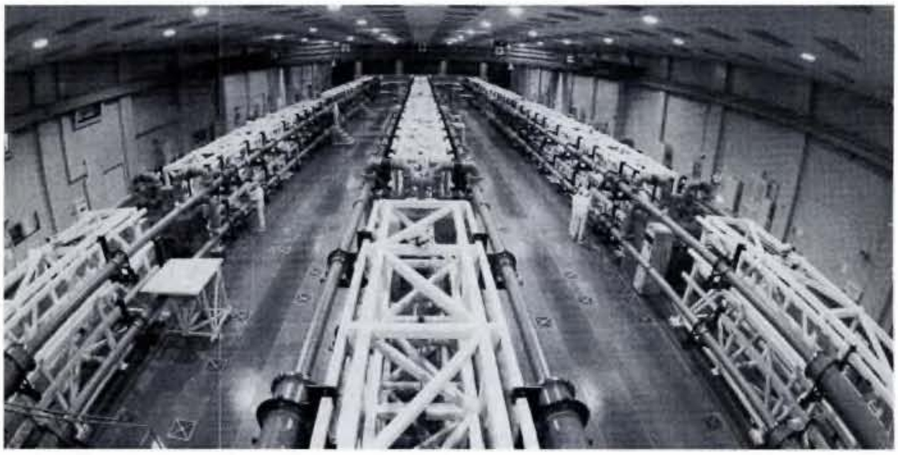

Fig. 6 — The Gekko-12 beam glass laser at the Institute for Laser Engineering, Osaka University.

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 4) 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.

This work was supported in part by the Commission of the European Communities in the framework of the Association Euratom/JPP.

REFERENCES

1. Zel'dovich Ya.B. and Raizer Yu.P., *Physics of Shock Waves and High-temperature Hydrodynamic Phenomena* (Academic Press, New York) 1966.
2. Pakula R. and Sigel R., *Z. Naturforsch.* **41a** (1986) 463 and *Phys. Fluids* **28** (1985) 232 (see also *ibid.* **29** (1986) 1340).
3. *Laser Program Annual Report 84*, Lawrence Livermore National Laboratory, Report UCRL-50021-84 (June 1985), available from NTIS.
4. Yamanaka C. *et al.*, in *Plasma Physics and Controlled Nuclear Fusion Research 1984*, Vol. 3, Nuclear Fusion Supplement 1985, p. 3; Okada K. *et al.*, *J. Appl. Phys.* **59** (1986) 2332.
5. Tsakiris G.D. *et al.*, *Europhys. Lett.* **2** (1986) 213. Herrmann P. *et al.*, *Z. Naturforsch.* **41a**(1985) 767; Földes I.B. *et al.*, *Europhys Lett.* **2** (1986) 221. Eidmann K. *et al.*, *Laser and Particle Beams* **4** (1986) 521.
6. To be presented at the 11th International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Kyoto, Japan, 13-20 Nov. 1986.

EPS PUBLICATIONS

The following are the subscription rates or prices for publications of the Society in 1987.

Europhysics News	
10 issues	Sw.Fr. 90.–
(free to IOMs and members of subscribing societies)	
Europhysics Letters	
24 issues (vols. III & IV)	Sw.Fr. 595.–
IOMs	Sw.Fr. 60.–
plus mailing contribution	Sw.Fr. 10.–
Europhysics Conference Abstracts	
Series 11 (8-10 titles)	Sw.Fr. 330.–
Previous subscribers	Sw.Fr. 290.–
European Journal of Physics	
4 issues (vol. 8)	£ 65.– or $ 110.–
IOMs	Sw.Fr. 55.–
Seminar on International Research Facilities	Sw.Fr. 65.–
IOMs	Sw.Fr. 40.–
Still Available	
Formulae and Methods in Experimental Data Evaluation (3 vols.)	Sw.Fr. 50.–
IOMs	Sw.Fr. 39.–
Proceedings of the:	
International Europhysics Conference on High Energy Physics, Bari, July 1985	Sw.Fr. 90.–
European Conferences on Controlled Fusion and Plasma Physics:	
10th Conf. Moscow, September 1981	Sw.Fr. 225.–
11th Conf. Aachen, September 1983	Sw.Fr. 175.–
12th Conf. Budapest, September 1985	Sw.Fr. 175.–
13th European Conf. on Controlled Fusion and Plasma Heating, Schliersee, April 1986	Sw.Fr. 175.–

Copies are available from the EPS Secretariat in Geneva.

EPS STAFF

On 1 September 1986 Andrew Fernandes joined the staff of the EPS Secretariat in Geneva as Assistant Executive Secretary as support for the Executive Secretary, Gero Thomas.

The new voice answering the telephone belongs to Christa Zurlinden.

EPS Divisions, Sections and Group
Astronomy and Astrophysics Division
  Solar Physics Section
Atomic and Molecular Physics Division
  Atomic Spectroscopy Section
  Chemical Physics
  Electronic and Atomic Collisions
  Molecular Physics
Computational Physics Group
Condensed Matter Division
  Liquids Section
  Low Temperature Physics Section
  Macromolecular Physics
  Magnetism
  Metal Physics
  Semiconductors and Insulators
  Surfaces and Interfaces
High Energy & Particle Physics Division
Interdiv. Group on Exptl. Phys. Control Systems
Interdiv. Group on Physics for Development
Nuclear Physics Division
Optics Division
Plasma Physics Division
Quantum Electronics Division

Europhysics News is the official journal of the European Physical Society which comprises 29 National Societies, Academies and Group, about 4000 Individual Members and 70 Associate Members. Governing bodies of EPS are the General Meeting, Council and an elected Executive Committee responsible for detailed policy. EPS promotes the collaboration of physicists throughout Europe, organising and harmonising conferences and publications, improving physics education, encouraging physics applications, awarding scholarships to sponsored schools in Erice. EPS publishes in addition to *Europhys. News*, *Europhysics Letters* (in partnership with national societies), *European Journal of Physics* (in partnership with The UK Inst. of Phys.), *Europhys. Conf. Abs.*, *Europhys. Ed. News*. Individual Members receive *Europhys. News* free of charge (price to insts.: Sw.Fr. 90.-/a), *Europhys. Lett.* at Sw.Fr. 55.-/a (insts. 550.-), rebates on many other publications and on conference fees. Annual EPS membership fee for Individual Members belonging to an EPS member society is: Sw.Fr. 44.-; independent members: Sw.Fr. 132.-; members of a Collaborating Society: Sw.Fr. 55.- ($ 26).

Editor: E.N. Shaw

Editorial Board:
K. Appert, A. Baratoff, F. James,
M. Mayor, J. Muller, M. Lehmann

Editorial and Advertising Office at the EPS Secretariat

Address: EUROPEAN PHYSICAL SOCIETY
P.O. Box 69,
CH-1213 Petit-Lancy 2
Switzerland

Telephone: Geneva (22) 93 11 30
Telex: 428 024 eps ch
Cables: europhys genève

Printed by: Pfirter frères sa
CH-1213 Petit-Lancy/Switzerland