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Research Cooperation with Past President Jak Kelly

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Abstract

A review of research work done in collaboration with Jak Kelly between 1975 and 2012 at the University of New South Wales requires a rather detailed explanation of the subjects covered. These begin with the pioneering work on very high intensity electron beams of energy ranging between 10 and 200 keV as well as ion beams and their defect generation in solid material. Combination with lasers led to the whole range of ion generation from few eV to GeV including the need for changing Maxwell's stress tensor of plasma optical properties. This led to the discovery of relativistic self-focusing and subsequently to joint applications based on papers covering solar cells and the reduction of friction in motor engines together with patents. With nuclear energy being 10 million times more efficient than chemical energy there is the possibility that lasers might lower the most dangerous levels of radioactive radiation to the point that it can be neglected.

Introduction

An indication of the importance of my collaboration with Jak Kelly is an obituary we prepared as fellows of the Institute of Physics (London) for its magazine, on Professor Christopher Milner, Head of the School of Physics at the University of New South Wales, and his long years of service (Hora et al. 1998). Milner was highly regarded for establishing the very successful School of Physics and for becoming the only physicist as Dean of Science. No doubt Jak Kelly was very appreciative when Kit Milner offered him an academic position in Sydney following the exciting work he had been doing at the Harwell Research Establishment in England. Jak's new position led to his appointment as professor and later to Head of the School of Physics and Chairman of the Faculty of Science of the UNSW.

Research in physics has numerous instances of adversity that cause friction and hamper progress. Never when working with Jak Kelly did I experience such negativity. If a researcher claimed to have measured velocities faster than *c* of light in a vacuum, Jak would a priori not take a negative stand and would first look into details for the claim.

Jak's interests followed many directions such as applying his profound knowledge to ion implantation or to defect generation in solids. Other directions were to investigate alternatives for energy generation and to deliberate on nuclear energy. During the times I collaborated with Jak there were many examples of the positive side to research. Although these personal reflections do not include Jak's contributions to areas such as solar-thermal energy production, or luminescence methods for measuring the age of pottery in archaeology, they do include *Electron Beam Treatment of Materials, Low Energy Nuclear Reactions, laser interaction with plasmas, and Nuclear Energy without Problems of Radioactive Radiation* that I have covered below.

Jak's positive attitude emerged at times when organisational decisions had to be made. For example the University of New South Wales was offered the purchase of the van-de-Graaf accelerator from the Australian National University when it purchased a new accelerator. It took Jak less than a second to accept the offer although there had to be a lot of work done before rich fruits of his decision could be harvested.

The following is a summary of results of our collaborative research. They reflect Jak's exceptional ingenuity and attitude to solving problems and even though not all problems were solved, in most cases the research helped to open new doors to knowledge.

Electron Beam Treatment of Materials

Electron beams could be seen long before the year 1900 in the electric discharges within low pressure Geißler tubes before one knew what an electron is. Using electron beams became more common in Braun's television tubes and by the wave properties in electron microscopes from about 1930. But to get the electron beams at such high intensities that these could melt materials, cut or weld them, came along only just around 1950. Jak Kelly's first publication was in Nature (Bruce et al. 1951) from work in Sydney about wave properties, and when he joined the University of Reading in England for his Ph.D. project, this was the place where the very intense electron beams were used. Metals with the highest melting temperatures above about 2000 centigrade could be heated up and liquid droplets could be studied. Kelly's paper (1959) described the "Electron bombardment apparatus for vacuum evaporation" leading to the first possibility to measure the surface tension of these materials (Tille et al. 1963) as basis of surface potential measurements (Townsend et al. 1967). On top it was highly important to study the crystal defects in materials by this bombardment of the electrons and also by beams of intense ions of similar high energies and current densities. About the crystal defects, a standard book was published by Kelly (Townsend et al. 1976, cited 350 times) and he became a leading authority in this field of high importance for material research when he was leading an international conference.

Similar but independent studies with high intensity electron beams came from another side for cutting and welding of metals under extreme conditions in Germany (Steigerwald 1961; Hora 1961). It was even possible that the basically fixed optical fundamental absorption of silicon could be changed (Hora 1961a). On top it could be shown that the very intense electron beams could produce defects in silicon for changing n-conducting crystals into p-conducting states producing diodes (Hora 1962) for later use for transistors at electron energies of 50 keV, while the established value by Lark-Horowitz from simplified crystal theory needed more than 200 keV. Another result with homogeneous semiconductors (GaAs) led to the calculation of the laser threshold at pumping with electron beams predicted (Hora 1964) exactly in agreement with subsequent measurements (Hora 1965a; 1965b; 1965c).

When I accepted the offer of the Foundation Chair in Theoretical Physics at the University of new South Wales in Sydney/Australia in 1975, I brought in this background for cooperation with Jak Kelly, though my appointment was based on my achievements of purely theoretical results. These were the clarification of the

Richardson equations for electron emission where the analysis on the basis of an integral equation led to the general spectral response theory of photoelectric electron emission (Görlich et al. 1957; 1957a; 1958) with the result that the general response function is given by a volume process in contrast to the established theory of the surface effect (Herbert Fröhlich; Igor Tamm). This was clarifying the unique property of the Cs_3Sb photocathode, discovered by Görlich 1936. This and similar compounds substituted soon all earlier emitters of photocells with the instabilities and low efficiencies. As another mathematical achievement, I had discovered the mechanical forces in plasmas by irradiation of light, if the correct dielectric optical properties were used (Hora et al. 1967) leading then to the exact modification of Maxwell's stress tensor in plasmas (Hora 1969). I solved the two coupled nonlinear differential equations for the complete relativistic motion of electrons in laser fields (Hora 1973) permitting the general solution of relativistic laser beams for self focusing in plasmas (Hora 1975).

This research background was well harmonizing with the interests of Jak Kelly though I was mostly involved with establishing lectures in higher mechanics, electrodynamics based on Maxwell's theory and the mathematical foundation for solving the Schrödinger and the Dirac equation for undergraduates, where I profited especially on my mathematical and theoretical education from German universities.

The sub-threshold energies of electrons for producing n- into p-conducting silicon was the first joint project to be studied with Jak Kelly, especially after I just got granted a patent (Hora 1977) how to produce solar cells by much lower costs and avoiding aggressive and poisonous chemicals. I had to win with a patent process against the AEG in Germany. This work was the topic of a Honour's thesis of Hinckley et al. (1979; 1980) supervised together with Kelly where the student received a first class honours and the University Medal.

Using the direction of crystal defect generation by ion implantation in silicon – pioneered by Kelly (Townsend et al. 1976) – I spend a study semester with the Siemens research laboratory in Munich-Perlach (Hora 1983) which results were then further studied at UNSW in cooperation with Julian Goldsmid and with using laser annealing by George Paul (Goldsmid et al. 1984) in cooperation with E.F. Krimmel (Siemens Research Munich-Perlach) about laser measurement of thermal conductivity. It should be mentioned that Goldsmid's work led to a widely used instrument for identifying diamond crystals.

For the ion implantation, it was interesting to use laser irradiated targets as sources about which I had experience from the laser-plasma interaction. In cooperation with Jak Kelly, J. Len Hughes from the Australian National University et al. we got granted a US-Patent (Kelly et al. 1980; 1981). This was then used for studies how to reduce the friction of iron after intensive and high energy implantation of tin ions. These studies were performed after I had become Emeritus Professor at the UNSW and had a Konrad-Zuse-Professorship in the Faculty of Electrical Engineering in Regensburg, Germany. These results (Boody et al. 1996) received more than 100 citations and through my contacts from the Rotary Club with the Regensburg plant of BMW, our research found interest by the R&D Chief, Dr.-Ing. Wolfgang Reitzle (BMW, Munich). The tin implantation reduced the friction in steel by a factor up to ten which result was measured by Savage (1984) at the University of Wollongong in contact with Jak Kelly. It was considered to improve motor engines for racing cars. The unique measurement by Savage (1984) led to the result, that when the iron surface was scratched off by friction under long use, the implanted tin ions are moving to the inner volume of the iron. We had no further information whether the interest was stopped when BMW withdrew from car racing or due to the fact that Reitzle had changed to become the CEO of Jaguar in England.

The production of very low cost solar cells with electron beam generated p-n junction was reported (Ghoranneviss et al. 2006) and an efficiency of about 10% at not optimized parameters was measured. This may open the production of solar cells in plastic foils of organic materials for an economic contribution to solar energy. The commercial level of present silicon solar cells is mostly determined by the high equipment and connections costs to be added to the present comparably high costs of the silicon cells. Kelly as the Editor-in-Chief of the Journal and Proceedings of the Royal Society of New South Wales during this time was interested and involved in reports and publications of related topics (Osman et al. 2007).

Low Energy Nuclear Reactions

This topic needs some introduction and explanation because this is related to the widely criticized "cold fusion". More than 95% of all what has been published since 1989 is unacceptable for physicists and it is important to select the few facts which may be taken seriously. The whole development came from a very important line of research, from the muon-catalysed fusion (Jones 1986; Rafelski et al. 1987). Along these lines of research, the incorporation of very large densities of deuterium in palladium resulted in the measured emission of neutrons (Jones et al. 1989). The confusion about these facts resulted from a press conference of Fleischmann and Pons on 23 March 1989 at Bingham Young University in Utah (Miley, see Hora 2011).

Jak Kelly's attention to these developments followed the results of Jones et al. (1989) by being involved from the early stages (Hora et al. 2001; Miley et al. 2009). Following the serious line of Jones and Rafelski, interesting physics approaches by Parmenter and Lamb jr. analysed Debye-length influences by the Thomas-Fermi-Mott model including the Oppeneheimer-Phillips process (Parmenter et al. 1989; 1990) and it may not have been a coincidence, that the evaluation of Coulomb screening was a key point of the work with Jak Kelly (Hora et al. 1993) which was later confirmed by ab initio quantum mechanics by Czerski et al. (2001) and Huke et al. (2008).

The present situation was summarized by a media source (Krivit 2013) in the following way: "The older researchers who have fought the battle for 'cold fusion' for 24 years have, sadly, found themselves with increasingly less funding, research, and mainstream media coverage. Their conference papers, for the most part, repeat the research they have done for many years. In some cases, they have presented the same experiments for a decade. During this time, they have made little progress, both in the expansion of scientific knowledge and toward commercialization of LENR technologies. On the other hand, something fascinating is taking place. As a result of slow but steady mainstream acceptance of LENR (by Royal Dutch Shell, Toyota Motor Corp., CERN, ANS, Boeing, ST Microelectronics, Elsevier, and Wiley and Sons), mainstream science and industry are taking notice."

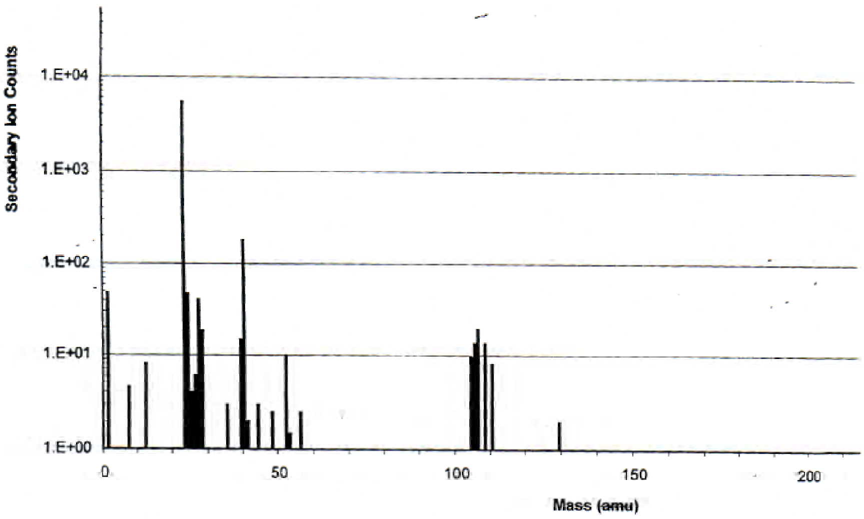

Figure 1a. Abundance of elements in palladium before loading with deuterium (Miley et al. 1996).

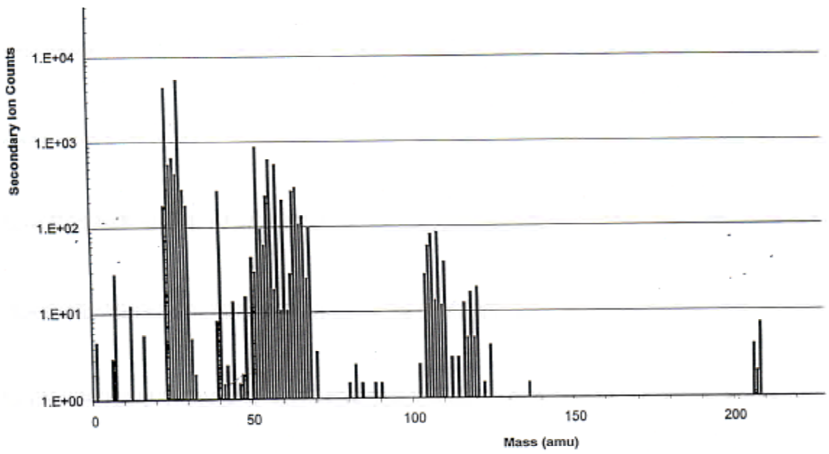

Figure 1b. The elements detected in palladium after electrolytic loading of deuterium.

In this situation it is necessary to give more detailed explanation to a rather complicate but completely solid basis for confirming the nuclear reaction mechanism when high densities of deuterium are incorporated in palladium or in comparable metals as nickel etc. before talking about the results established with Jak Kelly (Hora et al. 1993). The solid basis of the phenomena was given by Miley's et al. (1996) unique measurement of a Maruhn-Greiner Maximum (Hora et al. 2007). This can be mentioned as a well elaborated proof of the generation of nuclei from the whole list of stable nuclei up to lead, Figs. 1a and 1b. This discovery by Miley et al. (1996) has been documented as a "Low Energy Nuclear Reaction" LENR process. The distribution of the generation probability of the generated nuclei G(Z) on the nucleon proton number as discovered by Miley (1996), Fig. 2, which is similar to SAD (standard abundance distribution of elements in the universe, Rauscher et al. 1994; Hora et al. 1998) with a relation to the nuclear magic numbers (Hora 1998).

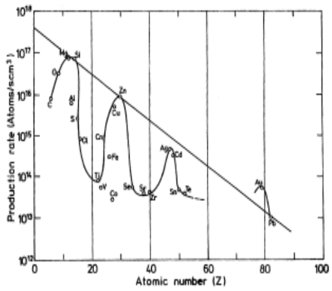

Figure 2. Generation probability G(Z) of elements with proton number Z after the reaction of the deuterium in the palladium (Miley et al. 1996, 2002).

When listing the distribution G(A) depending on the nucleon number A the minimum for A between 125 and 175, Fig. 3, this has a similarity to the distribution G(A) for the fission of uranium shown in Fig. 4. For Uranium 236 there is a large-scale minimum at A=118, just the half nucleon number of the Uranium nucleus (Feltus 2002). The splitting of Uranium nuclei is there from an unexcited state. However, if the heavy nucleus has been excited to energies around MeV, a local maximum appears for uranium as a local peak (Fig. 5 at A = 118) as it was theoretically explained by Maruhn et al. (1974).

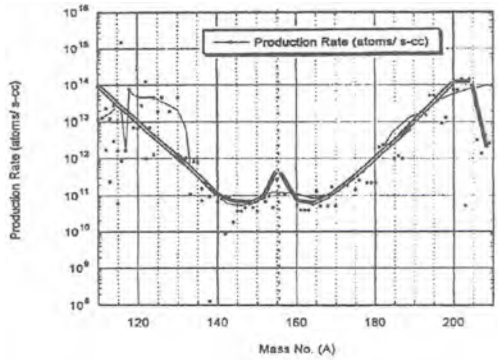

Figure 3. Measurement of Low Energy Nuclear Reactions (LENR) resulting in the distribution G(A) of the generation probability of nuclei of nucleon number A for the range between 125 and 185. Detailed nuclear mass spectrum of the LENR generation probability at the highest A-minimum with a local (Maruhn-Greiner) maximum at A = 155.

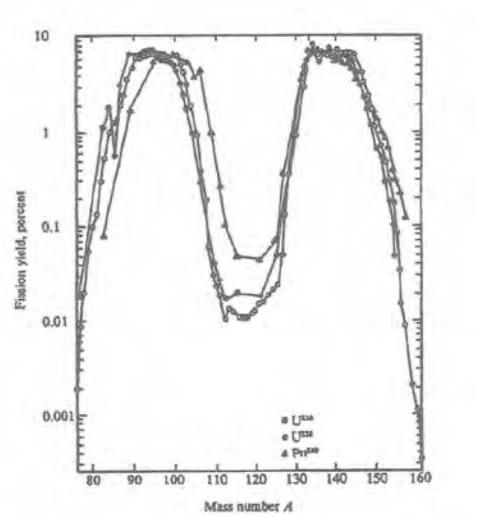

Figure 4. Distribution G(A) of the generation probability of nuclei of nucleon number A as measured from the nuclear fission of ^{233}U, ^{235}U and ^{239}Pu (Feltus 2002).

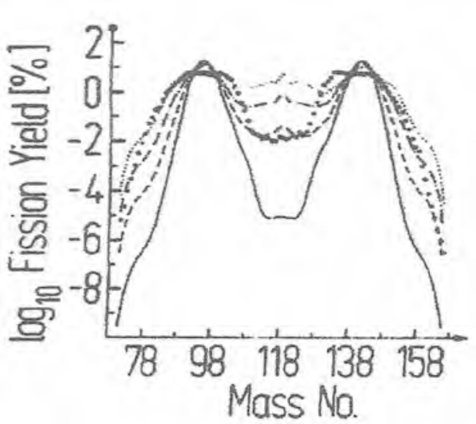

Figure 5. Fission mass distribution curves for ^{236}U calculated when the nucleus, at the time of fission, is excited to a temperature 0, 0.5, 1, and 7 MeV (upward sequence of Ref. Maruhn et al. 1974).

It is important to note for the case of deuterium in palladium, that a similar local maximum peak was seen in the measurement of the distribution G(A). At LENR (Miley et al. 1996) is a similar large-scale minimum at A = 155, Fig. 3 and *also a local maximum as a peak similar to the case of uranium fission of Fig. 5.* This fact of the observed Maruhn-Greiner Maximum (Maruhn et al. 1974) corresponds to a compound nuclear fission reaction (Hora et al. 1997; 1998a; 1998b; 1999; 1999a; 2000a; 2001) through a nucleus $^{310}X_{126}$ with Z = 126 protons and 310 – 126 = 184 neutrons. Both numbers 126 and 184 are magic nuclear numbers (Hora et al. 2001) and it is significant, that the evaluations of super heavy nuclei with Z between 116 and 120 have both numbers for well pronounced energy minima at 126 and 184 (Kuzmina et al. 2012).

Before Miley's discovery of the LENR process and how this was ascertained by the Maruhn-Greiner maximum, an important step was that with Kelly about the evaluation of *the plasma screening process for deuterons in palladium* crystals (see Fig. 1 in Hora et al. 1993) where the numbers for the reaction probabilities of Rafelski (see Jones et al. 1989) were completely fitting with a deuterium reaction in 2 pm distance. Different to most of the experiments with electrolytes, the measurements by Prelas et al. (1990) were loading palladium with deuterium in the gas phase or by plasma mechanisms. This permitted an evaluation by assuming that the deuterons in the palladium crystal were behaving like a Maxwellian gas and the theory of screening of Coulomb repulsion could be described in the same way as in the theory of Ichimaru (1994) for high temperature plasmas. In his case the Coulomb repulsion arrived at a reduction factor of 5. In our case (Hora et al. 1993) the screening has a factor of 13 according to the evaluation of experiments of Prelas et al. (1990). The Maxwellian deuterium ions are then, for distances down to 2 pm, behaving similarly to neutral particles. This agrees then to a reaction probability similar to the well-known inverse K-electron capture radioactivity. This reasonable property allowed considering that the deuterons can stick together at 2 pm distance as a Bose-Einstein cluster within which no locality of the deuterons is possible (Hora et al. 2007). The 10 pm diameter cluster reacts then with a palladium nucleus via a compound nucleus $^{310}X_{126}$ to fit with the measured Maruhn-Greiner local maximum. This result is based on the evaluation of the results of Rafelski (1987) and Jones et al. (1989) where Fig. 1 of Hora (1983) shows the reaction probabilities of Rafelski on which basis Kelly could evaluate reactions for D-D in 2 pm distance.

The phenomenologically derived screening by the factor 13 derived with Kelly in 1993 (Hora et al. 1993; 1996; 1998a) was confirmed from a complete quantum mechanical derivation (Czerski et al. (2001); Huke et al. (2008)). The long time uncertain question whether the LENR reactions emit neutrons of more than MeV energy from nuclear reactions was measured with recently developed diamond detectors (Prelas et al. 2012) resulting in a neutron emission of considerably more than one million within five minutes. These results led to the recent activities in industry laboratories for clarification of the mechanisms with the potential of far ranging applications.

Brian Josephson was interested in the physics of LENR and visited the UNSW 2005 after he had several times discussed these activities at the Nobel-Laureate meetings in Lindau/Germany. Attention was given by the team with Jak Kelly (Osman et al. 2005; Hora et al. 2005). He was at this time President of the Royal Society of New South Wales and arranged the then scheduled Pollock Lecture to be presented by Nobel Laureate Josephson and celebrated as a highly visited event.

Kelly's involvement in laser interaction with plasmas

Jak Kelly had joined the research team of laser interactions, including relativistic conditions and ion acceleration mechanisms, described in granted patents (Kelly et al. 1980; 1981) that were assigned to UNISEARCH, the commercialisation branch of the UNSW. This resulted in the first derivation of electric double layers in plasmas (Hora et al. 1984) and surface tension (Hora et al. (1989). The theory of relativistic self- focusing of laser beams in plasmas (Hora 1975) was the starting point for a number of studies. A further point of joint interest arrived about the topic of laser driven ion sources about which Jak was well familiar through his van-de-Graaf accelerator after it was successfully working. I had for more than one year a position as Attache Remuneree at the CERN Laboratory in Geneva/Switzerland with the aim, what can be done that the ion sources of accelerators may be improved by using lasers (Haseroth et al. 1993, 1996; Hora et al. 1992). Pioneering experiments were done before at the Russian high-energy physics research centre in Dubna well following the general developments on the main stream of laser-plasma interaction. This is the reason why it is necessary to summarise the related research in the following.

During my time at CERN, I was in close contact with Jak who had prepared laser work at his accelerator in combination to study the problems of laser driven ion sources. He had also prepared PhD students to contribute to this problem in cooperation with CERN, well following the concept of the earlier granted patents to UNISEARCH (Kelly et al. 1980, 1981). After successful experiments at CERN by a very experienced Postdoc from Munich (Hora et al. 1992) the later work by Russian colleagues did not lead at the expected results.

This research work on laser interaction with plasmas for ion generation is needed in the following to explain the development of ultrahigh acceleration of plasma blocks and of ultrahigh ion currents generated by nonlinear effects. The ultrahigh acceleration of macroscopic objects by more than 10^{20} cm/s^2 was the result of theory and computations at the UNSW (Hora et al. 1979a; Hora 1981) and was first measured by Sauerbrey (1996) who underlined that these acceleration were 100,000 times higher than ever produced in a laboratory before. The generated space charge neutralized ion macroscopic blocks had ion current densities above 10^{12} Amps/cm^2 (Hora et al. 2002) that were much higher than a million times than produced in classical accelerators. All these developments were considered in some contact with Jak Kelly leading then to his aspects (Hora et al. 2009) of a new scheme of laser driven nuclear fusion where the very dangerous radiation problems of radioactivity may be eliminated.

After these results with very energetic ion acceleration for all kinds of applications, it is necessary to differentiate against the basically different ultrahigh acceleration of plasma blocks by avoiding relativistic self-focusing. These are becoming important also for the application on laser driven fusion energy and are to be developed now for hadron therapy of cancers and other applications. This type of acceleration goes back to the early cooperation of the team including Jak Kelly as shown by his co-authorship for a scientific magazine (Hora et al. 2009) where theoretical-numerical predictions of 1977 from the UNSW (Hora 1991), however, needed a long time before the experimental verification was reached by Sauerbrey (1996). This was possible only after the radical new discovery (Strickland et al. 1986) of CPA (Chirped Pulse Amplification) permitted the generation of laser pulses with less than picosecond (ps) duration (down to attoseconds, Krausz et al. 2009) and with powers above petawatt (PW) (Mourou et al. 2006).

The developments go back to the effect discovered by Linlor (1963) of the crucial difference between thermal-chaotic hydrodynamic processes and the contrary basic nonlinearity determined mechanisms just opened by the laser leading to collective effects (Hora 2013). This touches the fundamental problems expressed by Edward Teller and are going to become under control by damping and stabilization of complex systems by Lord Robert May of Oxford (2011) following his Dirac Lecture in May 2011 which was supported by the RSNSW. For the stabilization mechanisms see the discussion about Edward Teller and Lord May in a recollection of Hora (2011). Before Linlor's discovery, laser pulses up to MW power when hitting targets in vacuum heated these up to plasmas of about 20,000 centigrade by classical thermokinetic pressures and fluid-dynamics, seen e.g., from the emission of ions of the corresponding energies if few eV. When Linlor applied very smoothly produced laser pulses of about 10ns duration by Q-switch techniques, the measured ion energies jumped from few eV to several thousand eV by changing the laser power by a factor of about fife only. The hope that then the laser driven thermonuclear fusion energy generation, however, could not be fulfilled, because the keV ions were not thermal but were linearly increasing on the charge number Z. Thermal processes would results in ions of same energy. The Z-dependence of the energy indicated an electrodynamic acceleration process, different from thermal action.

The action of electrodynamic forces goes back to the discovery by William Thomson (Lord Kelvin) who in 1845 discovered, that an electrical charge-free medium can be accelerated by divergent electrostatic fields. After discovery of Maxwell's equations, this ponderomotive force appeared also beyond electrostatics in time dependent electromagnetic fields, discovered by Weibel (1958) when electrons in vacuum could be confined within the nodes of standing waves of microwaves, and later by laser fields. The same could be concluded for space-charge neutral plasmas – similar to Kelvin's uncharged dielectric materials. The new situation for plasmas is due to the gradients of the optical dielectric and absorption constants (Hora et al. 1967) which were then just derived. The optical constants could be used for describing spatial variations of inhomogeneous dielectric plasma properties. This can be seen when a laser pulse penetrates a slab of plasma (Fig. 6) where the negative gradient of the optical constant results in forces moving the plasmas towards lower density.

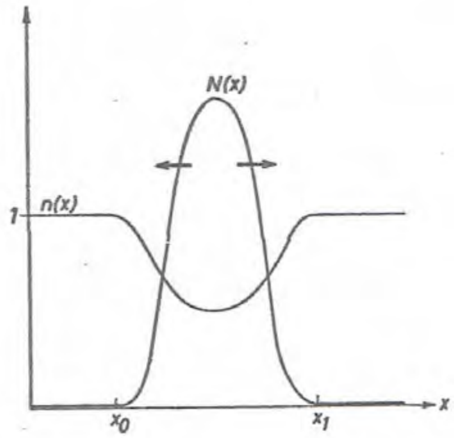

Fig. 6. Plasma layer between depths x_0 and x_1 with electron density N(x) and optical refractive index n(x). The negative gradient of n causes nonlinear (ponderomotive) forces (arrows) in the space charge neutral plasma (Hora et al. 1967).

The force density **f** in a plasma is given by the classical thermal gas-dynamic pressure $p=3n_pkT/2$ where n_p is particle density, k is Boltzmann's constant and T the temperature, and given by the nonlinear force $\mathbf{f}_{NL}$ due to electro-dynamic interaction

$$\mathbf{f} = -\nabla p + \mathbf{f}_N \qquad (1)$$

The nonlinear (optical corrected) nonlinear force was derived from Maxwell's stress tensor with the optical refractive index **n** for the stationary conditions from momentum conservation (Hora 1969) and for the general transient case with the unity tensor **1** and the electric **E** and magnetic field **H** of the laser:

$$\mathbf{f}_{NL} = \nabla\bullet[\mathbf{EE} + \mathbf{HH} - 0.5(\mathbf{E}^2 + \mathbf{H}^2)\mathbf{1} + (1+(\partial/\partial t)/\omega)(\mathbf{n}^2-1)\mathbf{EE}]/(4\pi) - (\partial/\partial t)\mathbf{E} \times \mathbf{H}/(4\pi c) \qquad (2)$$

from symmetry results (Hora 1985) for the final equation of motion (1) being Lorentz and gauge invariant (Rowlands 1990).

For simplified geometry with plane wave laser interaction, Eq. (2) can be reduced to

$$\mathbf{f}_{NL} = -(\partial/\partial x)(\mathbf{E}^2+\mathbf{H}^2)/(8\pi)$$
$$= -(\omega_p/\omega)^2(\partial/\partial x)(\mathbf{E}_v^2/\mathbf{n})/(16\pi) \qquad (3)$$

For high accuracy evaluations following the nonlinearity principle (Hora 2000) all components of the stress tensor need to be included (Cicchitelli et al. 1990). The first expression is the basic relation with the gradient of the electromagnetic energy density and the second expression is formally related to Kelvin's ponderomotive force, which was derived for electrostatics without magnetic fields and not for plasma properties. Following Eq. (2), the nonlinear force dominates over the thermal pressure, when the non-relativistic oscillation (quiver) energy of the electrons in the laser field exceeds the thermal energy

$$\varepsilon_{osc} = \mathbf{E}^2/(8\pi n_{ec}) > (3/2)n_e kT \qquad (4)$$

where **E** is the electric laser field and n_{ec} is the critical electron density n_e using the real part of the refractive index in the plasma $\mathbf{n} = (1 - \omega^2/\omega_p^2)^{1/2}$ which is zero when the laser radian frequency ω is equal to the plasma frequency $\omega_p = (4\pi n_e e^2/m)^{1/2}$ with the charge e and mass m of the electron.

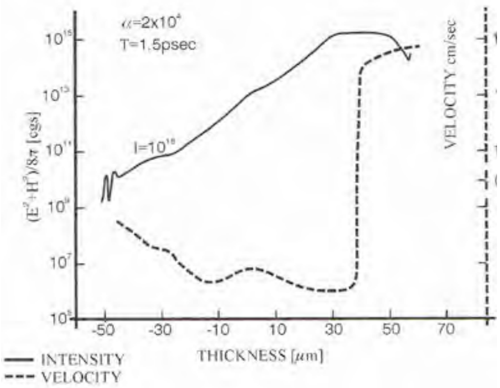

Fig. 7. 10^{18} W/cm² neodymium laser incident from the right hand side on an initially 100 eV hot very low reflecting bi-Rayleigh deuterium plasma profile, showing after 1.5ps interaction the electromagnetic energy density (Eq. 3). The dynamic development had accelerated the plasma block of 20 vacuum wave length thickness moving against the laser with velocities above 10^9 cm/s² and another into the plasma (combining results from p. 178 & 179 of Ref. Hora (1981)) with > 10^{20}cm/s² ultrahigh acceleration.

Using a general fluid-dynamic plasma-code with collisions, thermal equipartition between electron and ion temperature and with pressures with inclusion of the nonlinear force, the numerical result of Fig. 7 was achieved (Hora et al. 1979a; Hora 1981, p. 179) showing an acceleration of more than 10^{20} cm/s² of deuterium plasma against the laser light. In 1980, ps laser pulses with the high intensity were by far not available. But there was another reason that any experimental proof was impossible. The computations were performed with ideal plane geometry of the plasma target at plane wave laser incidence. Just at the time of the computations, the relativistic self-focusing was discovered (Hora 1975) such that any laser prepulse produced a plasma plume which squeezed the intense laser pulse to less than wave length diameter by relativistic self-focusing with subsequent very high ion acceleration into all directions (Basov et al. 1986; Häuser et al. 1988).

The situation changed drastically after the discovery of CPA (Strickland et al. 1986) when ps and shorter laser pulses above TW (Mourou et al. 2006) or 2 PW power (Cowan et al. 1999) were available. For technical reasons to produce the pulses without pre-pulses, their suppression by a very high contrast ratio was necessary to avoid the plasma plume. This led to the measurement of some strange plasma acceleration (Kalashinkov et al. 1994). A very convincing clarification by Sauerbrey (1996) was the measurement with similar pulses from very high quality KrF laser of 10^{18} W/cm² laser intensity, where the Doppler effect for the plasma front moving against the laser beam perpendicular to the target surface showed an acceleration of 2×10^{20} cm/s². This was in the range of the similar computer results with accelerations of Fig. 6 (Hora 1981), the more detailed evaluations (Hora et al. 2007a) were exactly reproducing the measurement of Sauerbrey if a dielectric swelling of the laser field of a factor 3 could be concluded, very similar to the comparable results by Badziak et al. (1999). The role of eliminating the pre-pulse was measured in a splendid way by Zhang et al. (1998) from the fact that the usually observed very high intensity hard x-rays at relativistic self-focusing were absent when using extremely high contrast. But if a ps pre-pulse was irradiated 70 ps before the main pulse, the x-rays were same as usual. The 70ps were calculated for the time to produce the plume. The repetition of the Doppler-effect measurement by Sauerbrey needed extremely sophisticated techniques and succeeded by Földes et al. (2000).

Sauerbrey (1996) underlined in the summary of his paper in order not to be missed, that his measurement of the nonlinear force driven plasma block – as theoretically-numerically expected since 1978 – was 100,000 times higher than any acceleration measured before in a laboratory. On top of the ultrahigh acceleration, a further result was (Hora et al. 2002) that the space-charge neutral plasma block consisted in an ultrahigh ion current density, more than million times higher than any accelerator could produce. This plasma block had the origin in the dielectrically strongly increased skin depth of the interaction by the nonlinear force. Its highly directed motion was in contrast to the ion acceleration by relativistic self-focusing which is going into all directions (Basov et al. 1986; Häuser et al. 1988). The directivity of the plasma blocks was experimentally confirmed as well as the plasma block behind the critical density (see Fig. 6) moving into the laser pulse direction (Badziak et al. 2004; Badziak et al. 2004a).

This overview of the general physical development of laser plasma interaction – as topic of discussions with Jak Kelly – explains not only how the points of applications had been developed, beginning with the work of radiation interaction (Hinckley et al. 1979, 1980) or the generation of energetic ions (Kelly et al. 1979; 1980) by laser interaction with targets, or the continuation for using as laser driven ion sources of accelerators at CERN (Haseroth et al. 1993; 1995). This was the topic of the discussions about the worldwide large-scale developments how lasers can lead to solve the problem of alternative energy generation without polluting the atmosphere with carbon dioxide CO_2. After long years developments, the just described discovery of the ultrahigh acceleration of plasma blocks led to an alternative method which was summarized in cooperation with Jak Kelly in a general article in a physics magazine (Hora et al. 2009), are summarized in the following section with an update for the recent developments.

Prospects of Nuclear Energy without Problems of Radioactive Radiation

The result of the ultrahigh acceleration of plasma blocks offered the possibility for a basically new scheme of generating low cost, unlimited, safe nuclear fusion energy and without the problems of generating most dangerous nuclear radiation as summarized by Jak Kelly (Hora et al. 2009). This was explained in more details in due course (Hora 2009; Hora et al. 2010; Miley et al. 2011) and follows the attempt to use the 10 million times more efficient nuclear energy production than available by chemical energy e.g., by burning coal, however with the goal that the emission of radioactive radiation including neutron generation per gained energy has to be of a lower value than from burning coal. This goal of ignoring the problem of dangerous radioactive radiation can be ignored, when burning protons with the boron isotope 11 (HB11) as fusion fuel in contrast to the usual fusion fuel of heavy and superheavy deuterium D and tritium T (DT).

In view that the emission of carbon dioxide into the atmosphere should be reduced by more than 80% of the present value, the need for alternative energy sources is of highest priority. Nuclear energy from the presently developed fission reactors is at present the second largest energy source while the managing of the radiation especially of the waste from the reactors and safety against unexpected incidents is solved to a very high degree but just not at a total 100% solution. On the other hand, energy from nuclear reaction processes is extremely interesting because the gained energy is more than 10 million times higher compared from exothermal chemical reactions. Despite an enormous amount of research, the aim of a fusion power station with controlled generated nuclear fusion is not yet at the level of break-even, even not yet for a power station with the easiest fusion of (DT).

The most advanced DT fusion process is that with nanosecond lasers pulses. If the lasers are heating and compressing the fuel to densities about 1000 times of the solid state, the thermal based process involves numerous losses and difficulties. The laser energy conversion into electrons is delayed by the collisions; then the thermal energy of the electrons has to be transferred by delaying equipartition processes into ion energy whose pressure is then determining the plasma dynamics. Instabilities and radiation losses are unavoidable (Hora et al. 1998c, 1998d). Nevertheless, the extension of all experiments with direct laser driving and adiabatic volume ignition led to the highest fusion gains (Hora 2013) and the extension of the results to nanosecond laser energy inputs of few megajoule from the largest laser on earth (Moses et al. 2008; Lindl et al. 2011; Haan et al. 2011) indicated that breakeven may be reached where the main advantage is the self-heat by the generated alpha particles and some self absorption of bremsstrahlung resulting in a jump of the volume ignition (Hora et al. 1978; 1998). The most studied indirect drive spark ignition has still nearly 1000 times too low gains (Hora 2013) and the self-heat is aimed for a solution. But even if this would be solved and one would consider the completely harmless final reaction products, the intermediary large amounts of neutrons, decaying with a half life of 12 minutes into stable end-products (electrons and water) have the problem of handling the tritium in the reactor and what during the 12 minutes life time is happening producing radioactive nuclei in the environment (Tahir et al. 1999).

A dream reaction is known from the beginning from the reaction of protons with the boron-11 isotope as being absolute clean. For the performance of laser driven fusion by the mentioned thermal processes by nanosecond laser pulses, compression to 100,000 times solids is necessary and all together this is about 100,000 times more difficult than the just not yet achieved thermal reaction with ns laser pulses.

The conditions are changing as it was shown at least from several computations with about same results from different approaches. With the advent of the nonlinear force driven ultrahigh acceleration of plasma blocks using ps laser pulses of PW power, the side-on ignition of a fusion flame in solid density fuel is possible now after the development of the CPA technique (Strickland et al. 1986; Mourou et al. 2006). The side-on ignition was the study by Chu (1972) and Bobin (1974) where a laser pulse irradiating solid density DT is leading to ignite a fusion flame. The computations of Chu resulted in the need of a minimum energy flux of 4×10^8 J/cm^2. This condition was far above the possibilities in 1972 and laser driven fusion energy followed the thermal compression and ignition of DT by nanosecond laser pulses (Moses et al. 2006; Lindl et al. 2011;

Haan et al. 2011). The conditions of breakeven can well be reached by direct drive volume ignition (Hora 2013) with 2 MJ nanosecond laser pulses due to a jump in gain by the self-absorption of alphas particles and by partial re-absorption of bremsstrahlung. This may now be a way also for indirect drive spark ignition (Haan et al. 2011).

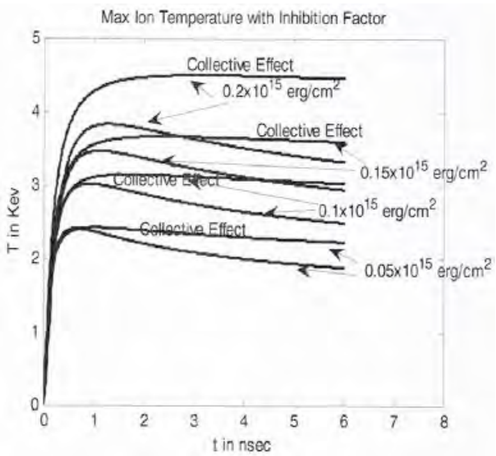

Figure 8. Dependence of DT plasma temperature T on time t after igniting by a ps deposition energy flux E given as the parameter to produce a fusion flame, generalizing the computations of Chu (1972) by using the collective effect for the alpha particle stopping and the inhibition factor for varying parameter of input energy flux density E*. Ignition is reached only above such E* where the temperature T does not decay on time t (Hora et al. 2008)*

An improvement of the flame ignition following Chu (1972) with updating of later discovered phenomena (Hora et al. 2008) (Fig. 8), arrived at the improved threshold for ignition of solid density DT-fusion of

$$E^* > 2\times10^7 \text{ J/cm}^2 \quad (5).$$

The result of the ultrahigh acceleration of plasma blocks (Hora 1981) when using CPA generated ps high intensity laser pulses (Sauerbrey 1996) led to the possibility (Hora 2009) to ignite solid density DT with laser energy fluxes above petawatt/cm^2, calculated for plane geometry (about other geometries, see below).

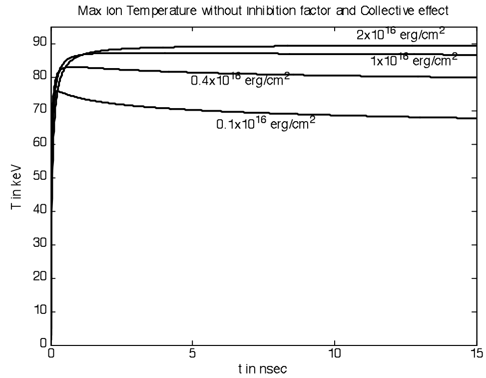

Figure 9. Temperature dependence on time t of the fusion flames for p-^{11}B (HB11) under the same assumptions of Chu (1972) for comparison with DT fusion. The 20-times reduction of E (Hora et al. 2008) is not included and the alpha stopping is as in the DT case only by electrons (Hora et al. 2009). The ion stopping with an avalanche of secondary production of alpha particles will lead to a much higher fusion gain for HB11 (Hora 2012).*

When the positive result for DT was applied to compute the case of HB11, it was rather surprising, Fig. 9, that the threshold for the side-on ignition was only 5 to 10 times more difficult than for DT (and not 100,000 times) (Hora 2009, Hora et al. 2009, 2010; Li 2010; Miley et al. 2011). On top, these computations were based on the Gabor collective alpha-stopping powers with electrons only as in the case of DT. The fusion gains will be dramatically increased if the alpha stoping includes the secondary ion interactions, where the resulting alpha particles all had the same energy of 2.88 MeV. When these alphas are colliding with boron nuclei, central collisions transfer 630 keV energy. This energy is in the wide range of an exceptional very large reaction cross section leading to a second boron reaction with a proton nucleus to produce three new alphas.

This multiplying avalanche reaction of the alphas can produce a gain very much higher than the gain from DT with the possibility to lead to an ideal burning of the fuel until exhaustion, depending of the detailed plasma fluid dynamics of the fuel after the ps-laser-pulse initiation of the fusion flame. The only bottleneck is the ignition by a laser fusion energy flux density of which at present it can be assumed that this is in the range of that for DT, Eq. (5), because this is a 2-dimensional process while the avalanche process is 3-dimensional.

Figure 10. For a new design ICAN (Mourou et al. 2013) of a CPA laser for pulses shorter than 1 ps and with powers of Petawatt to Exawatt and higher, the use of fibres is being designed with an initial partial section for demonstration of highest quality laser pulses on comparably low costs. The beam output of the fibre bundle irradiating a focusing mirror 6 has diffraction limited quality for focusing to highest intensities. It is expected (Mourou 2013) that a cross section of 100 cm² ps laser beam may be produced with kJ energy pulse corresponding to a Petawatt power.

The comparison between DT and HB11 for plane geometry and without the alpha-avalanche was only a first step of the computations (Hora 2009, Hora et al. 2009). What has not been included is that in the case of a fusion power station, only a (comparably large) section of plane geometry can be used for the interaction. A cylindrical section will suffer from lateral losses of energy and particles. One possibility to overcome this is to confine the cylindrical reaction by very large cylindrical magnetic fields (Moustaizis et al. 2003) after the shock processes in the fuel got under control in details from general plasma-hydrodynamics (Lalousis et al. 2013). This may be possible with the now available cylindrical magnetic fields above 10 kilotesla (Fujioka et al. 2013). Another way is to change from plane into spherical irradiation fronts (Hora et al. 2012; Moustaizis et al. 2013). In this case, however, ps laser pulses with a power above 100 PW are needed. 2 PW were achieved in 1999 (Cowan et al. 1999) and the level of 7 PW was reached in 2013. After the new scheme with fibre-optics accelerators ICAN (Mourou et al. 2013) in Fig. 10 can produce PW highest quality laser pulses at a cross section of 100 cm^2, a spherical irradiation of one meter radius may produce more than 900 PW laser pulses of 1 ps duration spherically propagating to extreme high intensities, see Fig. 11.

The conditions for initiating a spherical HB11 reaction depend on the result of Eq. (5) where a possibility may be to work with lower energy flux densities due to a small degree of avalanche alpha processes. The chance for this reduction, however, may be rather limited, because the initiation process in the ps range may be too short. The following evaluations are realistically based on the limit of Eq. (5) needing the operation with Exawatt laser pulses, though the total reaction efficiencies can be considerably much better than for DT. First evaluations resulted in gains of about 80 when generating 100 MJ fusion energy that up to 95% of which electrostatic conversion into electric power may be used. GW power stations may operate with less than about 15

Hz sequence of shots. The main advantage of working with sub-ps laser pulses consists in the collective conversion (Hora 2013a) of laser energy into macroscopic motion of the plasma blocks nearly without thermal losses in contrast to the spherical thermal compression and ignition of DT plasma being close to break-even (Hora 2013, Hora et al. 2013).

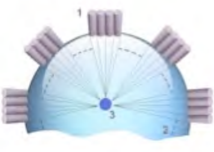

Figure 11. Combining the fibre output of an ICAN laser (Fig. 10) to a sphere (1) of more than 1m radius may produce a converging spherical laser pulse of 1ps duration and Exawatt power for interaction on a sphere 3 in the centre. Apart from diffraction limited beams with intensities above 10^{24} W/cm^2 for the application of HB11 fusion, the radius of sphere 3 can be in the range of 0.1 millimetre for producing nuclear energy in the range of 100 MJ free of neutrons and with less radioactivity per gained energy than from burning coal.

This is the present status for potential realization of BH11 power stations as envisaged by Jak Kelly (Hora et al. 2009) following the comment of an expert in nuclear fusion at the Lawrence Livermore National Laboratory in California, S.W. Haan (2010) "This has the potential to be the best route to fusion energy".

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