

## A life for laser driven inertial confinement fusion

Heinrich Hora

Department of Theoretical Physics, University of  
New South Wales, Sydney 2052, Australia

After having learnt computer programming with stone age machine codes up to fortran at IBM and leaving behind some early success on radiation emission from solids and on semiconductor physics, I joined the Institute for Plasma Physics (later Max-Planck-Institute) in Garching/Germany in October 1962 with the aim to study laser-plasma interaction for inertial confinement fusion using an IBM 7600 machine. First I had to learn plasma physics where I showed how the complex optical constants from Schlüter's two-fluid equations could be derived with Spitzer's collision frequency arriving at the basically same values as the derivations from quantum electrodynamics (Gaunt) used in astronomy and same values from the inverse bremsstrahlung theory. To treat laser-plasma interaction I could use my preceding work on electromagnetic wave propagation in inhomogeneous media where I used exact solutions with elementary functions for Rayleigh profiles and more generally the WKB approximation.

With these tools I could approach the laser-plasma interaction theory for fusion applications after I saw from primitive fusion estimations what rather confusing predictions on fusion resulted. Having witnessed the lecture by Basov and Krokhin at the UNESCO center in Paris at the Quantum Electronics Conference February 1963 and having seen the Westinghouse report by Albert Engelhardt very similar to the later seen reproduction of the Basov-Krokhin paper by John Dawson – well appreciating some numerical extension by Dawson - I used their self similarity model for the hydrodynamics and my results on optical plasma properties to perform systematic laser fusion computations for adiabatic expanding plasmas. The input was a uniform initial maximum plasma density  $n_0$  expressed in multiples of the solid state density  $n_s$  where the spherical plasma had received an energy  $E_0$  expressed in relation to a break-even energy  $E_{BE}$ . Using the well known fusion cross sections for DT (deuterium and tritium), I found an agreement with the few cases calculated by Basov and by Dawson. These values showed very low gains of fusion energy, but by systematically computing cases with varying parameters I found the best optimum values published in my Institute's Report in July 1964 (translated in Canada in 1965) of which two pages are presented here as my very first publication on laser fusion. My computations for various densities and energies resulted in the plots with the parabolic

curves in the mentioned IPP-report arriving at the highest gains  $G$  according to

$$G = (E_0/E_{BE})^{1/3}(n_0/n_s)^{2/3} \quad (1)$$

The optimum DT plasma temperature was found to be 17 keV (about 197 Million degrees Kelvin)

What was downcasting and disappointing was that the break even energy  $E_{BE}$  was about 6 MJ (mega joule) while the best Q-switched lasers at this time had pulses of few Joules for few ns (nanosecond) duration. On top the gain increased on the cubic route of the input energy  $E_0$  only. But what was evident from formula (1) was that an increase of the initial density e.g. to 1000 times the solid state needed then one million times less energy  $E_0$  to reach the same gain. Therefore "compression" was the key word which was well known from uncontrolled fusion reactions.

This gain formula (1) is algebraically identical with the formula  $G = \text{const}5n_0R$  (where  $R$  is the radius of the spherical plasma compressed to the initial density  $n_0$ ) which was published by Ray Kidder in 1974 after my formula had been published at several places before, e.g. at the Quantum Electronics Conference in Osaka 1970. I even was the referee for Kidder's publication in Nuclear Fusion but I was too timid to insist "that the author should first confirm that his const. agrees with my earlier values". Indeed I had checked that there was an agreement within a factor two and recommended publication. Later, my first book about laser fusion 1975 was knocked down by Moshe Lubin with the argument that I did not use Kidder's formula but only my algebraically identical however much more transparent formula (1). Indeed the use of compression was fully familiar to John Nuckolls at Livermore from his classified work which partially was declassified by the famous lecture 1972 of Edward Teller at the Quantum Electronics Conference in Montreal. Nuckolls had most pioneering results since 1960 and showed his unquestionably correct gains at 10,000 times solid state density in 1972 what was fully wrongly criticised by others later.

These computations seemed to be rather convincing and without difficulties if there was not the question, how to get the energy  $E_0$  uniformly into the compressed plasma sphere. When performing the first laser-plasma experiments after the clean Q-switch laser pulses were available in 1962 through Hellwarth at the Hughes Aircraft Laboratory in Malibu, a crucial new area in physics was opened: nonlinear physics. Before, the laser pulses of up to 1 MW power irradiating targets showed fully classical interaction. The targets were heated to temperatures

of of about 30,000K and the emitted ions had the expected energies of up to few eV (electron volts). When Linlor next door to Hellwarth irradiated with 10 MW, suddenly he measured huge amounts of highly charged ions of up to 10 keV energy which just is necessary for nuclear fusion of DT. Linlor was immediately promoted to the Atomic Energy Commission in Washington to work on laser fusion. But it turned out that there was not the expected temperature of above 100Million degrees Kelvin, the plasma still remained at very much lower temperatures and it was just a new kind of ion acceleration due to unknown processes which were shown to be essentially nonlinear. Characteristic to this was that the large number of oins (much larger than ambipolar processes could explain) were separated linearly by their energy on their ion charge number Z, what therefore was typically for a non-thermal process.

In order to follow this up, I looked into the optical properties of laser-plasma interaction, especially what the variation of the refractive index in the inhomogeneous plasma corona does with respect to electrodynamic interaction forces. Indeed a force of this kind was known as electrostriction by Kelvin since 1846 reformulated later by Helmholtz as “ponderomotive” force in electrostatics. For high frequency fields, Erich Weibel was the first to see formally the same forces proportional to the negative gradient of the electric field vector  $\mathbf{E}$  (force density  $\mathbf{f}_{NL} \propto -\nabla E^2$ ). For the dielectric properties of plasmas, I found the first approach using the fields in inhomogeneous plasmas. My boss, Arnulf Schlüter did not believe me. Only thanks to the moderation of Dieter Pfirsch who was enormously gifted in listening and understanding most complex physics, we came to the result of the nonlinear force density, published early 1967, which expression as the gradient of energy density was formally comparable with the ponderomotive force for simplified geometries.

At this time, Ray Kidder in Livermore led a very interesting experiment with spherical irradiation of 16 laser beams on a spherical target. From this group a paper by Gregg and Thomas was published about the usual observation of the keV ions, but Kidder tried to see the spherical compression. Instead, the sphere produced plasmas moving each like spikes against each laser beam such that the plasma looked like the fruit of a chestnut. I was there end of 1966 from an APS conference in Stanford and was led to the Livermore experiment. I had to pass three gates with barbed wires and my photo and the finger-print was checked. Kidder came and asked me a number of

questions on my work. When I tried to ask a question, I was told this cannot be done.

By the way, following my results in the IPP 6/23 report I submitted a patent with Benedikt Kronast on laser fusion. This patent was classified and I had, as German citizen, to sign to be quiet or to be punished up to the electric chair. Later the patent was declassified and granted in the USA (3444377) and other countries.

In order to understand the strange laser-plasma interaction, I could first conclude the linear Z-dependence of the acceleration of the very energetic ions and could suggest how the nonlinear force dielectrically was getting the plasma corona to a non-thermokinetic (low temperature) explosion into a part of plasma moving against the laser light and another plasma block moving into the plasma interior with the keV (and later MeV and GeV) energies. I was then invited to join the experiments of Engelhardt at Westinghouse where I could in all details quantitatively analyse their excellent experimental results by ordering the numerous parameters to see the gas dynamic interaction with clear spherical plasma expansion and the energetic nonlinear force driven plasmas. This was published in the first volume of Laser Interaction and Related Plasma Phenomena (LIRPP) of which Plenum Press sold more than 1500 copies.

My appointment at Westinghouse was tenured as a Senior Physicist with all privileges of pension etc.. The laser fusion project was then stoped due to the financial problems of the US in Vietnam. I could have continued at Westinghouse on a project which I had published on defect generation in solids, I got offered a deputy director’s position at a Fraunhofer Society on semiconductor physics and an offer as Associate Professor at Rensselaer Polytechnic Institute but I followed up my position at Garching from where I was on leave and where I could continue on laser driven ICF. I could work part time at the position at Rensselaer founding there the conference series “Laser Interaction and Related and Related Plasma Phenomena” apart from other research (Schwarz-Hora effect; Goos-Haenchen effect for Schrödinger waves etc.).

A problem arose end of 1969 with the politics of Willy Brandt in connection with the non-proliferation treaty when my statements of laser fusion supported the arguments of the opposition of Dr. Franz Josef Strauss with consequences for Switzerland, South Africa and others. My difficulties with the red court camarilla of Brandt (which seemed to be more oppressive than that under Kaiser Wilhem) lead me then to accept the foundation chair of theoretical physics at the University of New South Wales in

Sydney/Australia to establish a new department and where I with several research students, guests and some associates in my department could work on laser fusion with good outside support.

An essential progress in 1969 was with the PhD thesis of J.W. Zink supervised by James Shearer at Livermore within the project of Kidder at Livermore. Numerically it was shown how the nonlinear force of a  $10^{16}$  W/cm<sup>2</sup> neodymium glass intensity irradiating an initially linearly increasing ramp of plasma, is creating the fast plasma block moving against the laser light and how a density minimum is generated near the critical density which later was called a caviton together with a steepening of the density profile to the plasma interior. This important numerical discovery was then the convincing tool to measure the cavity as proof for the action of the nonlinear force. This succeeded so splendidly with microwaves by Wong and Stenzel and then with lasers by Zakharenkov et al, by Azechi et al and many other groups.

Another experimental confirmation of the nonlinear force was the measurement of the electrons emitted laterally from a laser beam focused in tenuous helium at  $10^{16}$  W/cm<sup>2</sup> neodymium glass laser irradiation by Bruce Boreham (Phys. Rev. Letters 42, 776, 1979). The maximum electron energy of about one keV corresponded exactly to the value expected from the nonlinear force. The polarization independence agreed also with the result  $-\nabla E^2$  for the force. When one, however, was trying to see how the quiver motion was converted into translative motion, the energy of keV was reproduced only into the E-direction of the laser field, and not any acceleration was along the H-direction if the laser field was presented as being fully transversal by cutting a Gaussian profile from a plane wave field. This led to recognize that this laser field was not Maxwellian exact and that it had surprisingly a very little *longitudinal* component to be exact. With this tiny addition, the computation of the electron motion along H changed from zero to the keV. This led to realize the *nonlinearity principle*: the neglect of very minor linear physics parts can change a result from wrong to right, from yes to no! Nonlinear phenomena are therefore not a higher order extension only with some percentage corrections of results, but can totally confuse results. We knew into what direction we had to look and solved the problem (PhD Thesis of L. Cicchitelli: Phys. Rev A41, 3727, 1980) with a better understanding of laser beams (PhD of R. Castillo). Otherwise realizing this principle opens the possibility that in future we can systematically derive phenomena of which nobody could have dreamed of with fundamentally new applications in life and

society. We have then to explore linear physics to even higher accuracy and expand mathematics and computations enormously for systematically exploring this nonlinear physics. A basically new dimension of physics is then opened. This is in contrast to the expectation of saturation of physics knowledge and the end of physics concluded by Steven Hawkins or Carl Friedrich von Weizsäcker.

The general derivation of the nonlinear force (Physics of Fluids 12, 182, 1969) from my Westinghouse time led to the discovery of two extra nonlinear terms additional to the one which Schlüter had derived in his space charge neutral two-fluid hydrodynamic equations. Indeed he had derived (in contrast to Spitzer) the other nonlinear term which achievement was extremely difficult but he mastered it. For me, the derivation was not so difficult since I knew from momentum conservation at laser-plasma interaction, what was missing. The only printed derivation of the so completed space charge neutral hydrodynamic equations is only in my books (Plasmas at high temperature and density, ISBN 0-387-54312-0, Laser Plasma Physics ISBN 0-8194-3509-0 and a textbook on electrodynamics ISBN 3-89073-749-8). Schlüter mentioned recently that he still does not believe in my result.

For the time dependent nonlinear force, the first theory came from Klima and Petrzilka (1972) in agreement with the formulation for plane geometry. For the general case a hefty controversy appeared with six groups having six different formulas including ter-Haar, Washimi, Karpman, Tskhakaya, Kono and others. With a rather unusual polemic interpretation to this confusing situation, it was nearly solved by the work of Zeidler, Mulser and Schnabl, but only “nearly”. A very small logarithmic term was still missing which I found from algebraic symmetry (Physics of Fluids 28, 3706, 1985). The final completeness of this and only this formulation of the nonlinear force was proved in a thesis by Rowlands (1990) from Lorentz and gauge invariance.

With these results I derived the first theory of ponderomotive self-focusing (1969) showing why the laser-plasma interaction changes at MW laser intensities from the classical gas dynamics into the nonlinear physics range. My general theory of the relativistic self-focusing (1975) – expanded by the PhD work of E.L. Kane (Phys. Fluids 1982) and the PhD of T. Häuser (Phys. Rev. A45) - could explain exactly why ions with energies above MeV were measured from laser produced plasmas (Ehler, Luther-Davies) then for the first time. Another triumph of the nonlinear force was when Francis Chen in 1974 could derive in a very general way that the numerous parametric instabilities at laser-plasma

interaction were all due to the nonlinear force. My result of 1969 contained also the momentum flux density of the electromagnetic energy in the inhomogeneous plasma and the result that this was half of the Abraham and half of the Minkowski formulation. This led to the solution of the Abraham-Minkowski problem at least for fully ionised plasma (PhD of M.M. Novak).

Back to the computations of fusion gains, it was evident how poor our formula (1) and the equivalent later one of Kidder was. No fuel depletion, no self-heat by the reaction products and no re-absorption of the bremsstrahlung in the reacting plasma was included what we all then followed up. Essential was the inclusion of a collective stopping power theory with which we could immediately explain the measured (Kerns et al, Kirtland Air Force Base) very anomalous short stopping length of relativistic electrons in plasmas. We learnt later that this collective model was derived before by Denis Gabor (1953) in contact with the pioneer of plasma theory, S.R. Milner who before Debye had derived the Debye length. Our work (PhD thesis of P.S.Ray 1977) led to the discovery of the volume ignition of a laser heated and compressed spherical plasma (1978). This result was confirmed in 1971 by R. Kirkpatrick and John Wheeler and showed that nearly the same high fusion gains could be achieved by the “robust” volume ignition (Colgate, Lackner) in contrast to the hope of fashionable central spark ignition with its very non-natural temperature and density profiles and difficulties with symmetry and instabilities. Very sophisticated extensions and improvements of the volume ignition by Martinez-Val, Eliezer, & Piera and by Xiantu He & Y.-S. Li) should be mentioned. After McCrory publicly ridiculed my initial computations by claiming that I were cheating by using wrong constants, we published an extended version of the code (Stening et al, LIRPP10, 1992) such that everyone can convince him(her)self what was calculated.

One triumph is that the highest ever published direct drive fusion gains from Osaka, Livermore, Arzamas-16 and Rochester fully agree with our shock- and stagnation-free volume compression computations (J. Plasma Physics. 60, 743, 1998). It should be mentioned that Mike Campbell - familiar like nobody else with all details of spark ignition and laser technology - commented Dec. 2004, that the mentioned agreement may be due to the low quality laser pulses at Osaka and Rochester. Nevertheless the mentioned Livermore (Shiva) direct drive result was fitting volume burn in the same perfect way as the others in contrast to fast pushers where their strong shock generation prevented high gains.

Hydrodynamic codes were developed to study details of the nonlinear force interaction in plane geometry following the mentioned success by Shearer Kidder and Zink with the WAZER code from early 1970. Rick Kinsinger at Rochester developed a very detailed code where the exact electromagnetic wave field in the plasma corona was used on top of a one-fluid different electron and ion temperature and mutual coupling description. I had to add only nonlinear generalizations of the optical constants and – as main part – the inclusion of the nonlinear force. The result for irradiation of deuterium with initially linearly increasing density along 50 wave length before critical by up to  $10^{18}$  W/cm<sup>2</sup> laser pulses – mostly done later in a PhD thesis by Vincent Lawrence – showed a very depressing result. The light was initially reflected at the critical density (mirror reflection) with a low net reflection due to absorption along the plasma corona. The partially reflected light field caused standing waves through which the hydro-motion of the plasma was too slow to pass such that the nonlinear force produced a density ripple within few ps and then a high von-Laue-Bragg reflection appeared as a phase reflection at the very low peripheral densities prohibiting the laser light to deposit its energy into the plasma. The plasma did all to prevent heating: Moshe Lubin was very depressed.

Fortunately the WAZER code was rather primitive and did not include the whole wave field with the reflection, otherwise Shearer, Kidder and Zink would not so easily have discovered the caviton. The change between mirror and phase reflection could be seen (Lubin 1974 “Phys. Rev. to be published” which never was printed!) from the stochastic change of the measured net reflection between few percent and longer periods of 10 and more ps of high reflection. We considered to prepare a patent with phase modulation in a ps scale, but this did not proceed. Maybe that this was in the air around 1980 when Kato was in Rochester and where his discovery or the random phase plate was introduced to suppress ponderomotive self-focusing and filamentation. Finally it turned out that this beam smoothing was eliminating the density ripple and the phase reflection in order to get high energy input into the plasma (Phys. Rev. A45, 6123, 1992). Indeed the stochastic pulsating interaction on the 10 ps scale was measured independently from this all by Luther-Davies and Maddever 1988, to which the mentioned ripple suppression was the numerical confirmation when using random phase plates. This permits then to use red laser light with appropriate smoothing for direct drive instead of using expensive higher harmonics generation. This suppression of ripples

also suppresses parametric instabilities by a factor 100 as confirmed experimentally by Guiletti et al (LIRPP9, p.261) leading to an increase of direct driven fusion by a factor 50 (Azechi et al, Laser and Particle Beams 9, 167, 1991)

For plane wave interaction we developed a genuine two-fluid code where the electric coupling between the electrons and ions was included (PhD of P. Lalouis). This gave revealing insights for the coupling of the laser field with the longitudinal plasma oscillation and the generation of quasi-Langmuir waves (due to the inhomogeneities no longer waves, only quasi-waves) showing all details of electric double layers numerically, even the inverse double layers at cavitons (Phys. Rev. Letters 53, 1650, 1984). More analytical results could be derived generalizing ambipolar phenomena with nonlinear terms, e.g a new resonance at perpendicular incidence and long wave length structuring at the low density corona (PhD. M. Goldsworthy) as observed (Gu Min and Aleksandrova, Brunner, Sklizkov et al) and being suppressed following our theory.

The double layer theory led to the derivation of surface tension of plasma, stabilization of surface waves at short wave length, explaining why the measured Rayleigh-Taylor instability is less dangerous than all established theories claim. The generalization to the degenerate electron gas (R.S. Pease et al) arrived at a direct quantum theory of surface tension of metals and generalising this to the Fermi-Dirac energy of nucleons leads to a new theory of nuclear forces based on a kind of Debye length (SPIE Proceedings 5448, p. 1190) explaining why endothermic nuclear synthesis is possible under equilibrium only to about uranium and why at six times higher than nuclear density the then relativistic branch of the Fermi energy of nucleons prohibits nucleation and the quark-gluon soup is produced. It also explains the jump in Bagge's series for the magic nuclear numbers without needing the Jensen & Goepfert-Mayer solution. And this all is a consequence from the ugly and only low level classically degraded plasma physics!

When Azechi et al in 1991 measured laser compression of polyethylene by lasers to 2000 times the solid state density, an unexpected low temperature of 300 eV (348 Million degree Kelvin) only was measured against expected much higher values. Hopes for laser fusion were disappointed. It was Mike Campbell who had the idea that the just then discovered CPA technique to produce ps-PW laser pulses could be used to add up the necessary heating after the enormous compression which scheme as fast ignitor was then developed in cooperation with Max Tabak and others. An

alternative to the result of Azechi et al was that we recalled our volume ignition computations where at sufficient large laser pulse energies and sufficient high compression, the ignition temperature could well be near 500 eV and even lower. One result is that if compression could be increased from 2000 to 5000 times the solid DT and if a red smoothed neodymium glass laser pulse of 10 MJ (twice that of NIF) is incident that the gain of 140 (fusion energy per incident laser energy) can be achieved by volume ignition (J. Plasma Phys. 69, 413, 2003).

The research for the fast ignitor as initiated by Mike Campbell is now a broad stream of research worldwide. The irradiation of the laser on a target usually has a prepulse which is leading to relativistic self-focusing as measured in the numerous experiments since 1975 and fully understood by theory, see above. The petawatt pulses resulted in relativistic effects never seen before as large amounts of positrons from pair production, gamma bursts of 10 MeV and higher energy producing nuclear transmutation by nuclear photo effect, ion energies in the GeV range and electron beams in the 100 MeV range (Laser and Particle Beams 18, 135, 2000) etc.. Within this broad stream of research there were some very special exceptions. There were the measurements of Badziak et al in 1999 on ion emission by TW-ps laser pulses where instead of the expected 22 MeV  $\text{Cu}^{+10}$  from relativistic self-focusing as seen in all similar experiments, the ions had an energy of half MeV only. When varying the laser intensity by a factor 30, their energy changed in the same way, but the ion number was completely unchanged. The explanation (Opt. Comm. 207, 333, 2002) was as clear as simple: there was no sufficient prepulse to generate a plasma in front of the target to permit relativistic self-focusing and the interaction occurred only in the (nearly) constant volume of the skin layer.

This skin layer acceleration of plasma was then confirmed in detailed experiments and computations. It was helpful to remember the  $10^{18}$  W/cm<sup>2</sup> plane geometry computations for ps duration (PhD. V. Lawrence 1978) where such a skin layer acceleration (SLA) by the nonlinear force within 2 ps was shown. A several wave length thick deuterium plasma block was moving in a very directed way against the laser and another block into the target. As expected 2002, these nearly space charge neutral blocks had ion current densities up to  $10^{11}$  Amp/cm<sup>2</sup> as measured then and reproduced by computations in all details (Appl. Phys. Letters 85, 3041, 2004). The fact that the prepulse was sufficiently suppressed (contrast ratio  $10^8$  until 50 ps before the main pulse) was seen very convincingly in a paper by Zhang et al (Phys.

Rev. E 57, 3746 (1998)) where the x-ray emission from targets at 100fs-TW Ti:sapphire laser irradiation was measured. These x-rays were of unexpected low intensity in contrast to all the usual experiments (where indeed prepulses permitted relativistic self-focusing the subsequent extreme high intensities necessary for the high x-ray emission). When similar 7% intense 100fs pulses were pre-irradiated at varying times, nothing changed 20 to 50ps precursor time. But at 70ps and longer times, the usual high x-ray emission was seen. The 70 ps prepulse permitted the establishing of a plasma plume necessary for the relativistic self-focusing as usual.

An experiment by Sauerbrey (1996) using a TW-0.3ns KrF laser pulse focused to about 30 wave length diameter as usual on a target, showed an acceleration of the plasma front by  $10^{20}$  cm/s<sup>2</sup> from Doppler measurement. Exactly this was calculated by nonlinear force acceleration for an undistorted plane plasma front confirming indirectly that there was not sufficient prepulse to produce self-focusing. When Sauerbrey tried to repeat this later with Ti-Sapphire laser pulses, no similar Doppler shift was seen. Obviously the prepulse in this case resulted in self-focusing and destroyed the plane geometry conditions.

The measured low temperature plasma blocks of about 30  $\mu$ m diameter width,  $10^{11}$  A/cm<sup>2</sup> DT ion current densities with resonance-adjusted 80 keV energy could be considered for ignition of uncompressed solid DT. Similar low compression large amount DT was considered by Nuckolls and Wood (2002) to be ignited by electron beams as a fast ignition experiment. In our 80 keV DT block ignition, a 10 kJ laser pulse could well produce 100MJ fusion energy in a fully controlled way (SPIE Proceedings 5228, p 295) similar to the before mentioned case with electron beams but avoiding any complication of pre-compression. A necessary condition for the de-classified SLA-nonlinear force block ignition is that the laser pulse energy is high enough. The Badziak et al experiments are close to  $10^6$  J/cm<sup>2</sup>. The necessary condition of  $4510^8$  J/cm<sup>2</sup> (Bobin 1971) should be available with shorter laser wave lengths while not destroying the other conditions. Whether this may lead to a new modified direction of Campbell's fast ignitor for a very simplified fusion power reactor is just under discussion.

Added:  
Portrait of author

Fig. 1: title page of English translation (1965) of the Report 6/23 (July 1964) of the Institute of Plasma Physics, Garching, Germany  
Fig. 2: Figure on DT nuclear fusion gains of the 6/23 report.