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Summary of the International 'Dawson' Symposium on the Physics of Plasmas

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Abstract

The 'Dawson' Symposium was held on September 24 and 25, 1990 in honor of John Dawson's 60th birthday to reflect on various physics of plasma that he had pioneered. The international speakers touched on a wide range of subjects: magnetic fusion, laser fusion, isotope separation, computer simulation, basic plasma physics, accelerators and light sources, space physics, and international scientific collaboration. Highlighted in this article are magnetic fusion and laser fusion investigation that Dawson has been engaged in and the reviews of the present status of their development. The impact of the two-component fusion plasma idea, reactor concepts for advanced fuels, hot electron production by lasers and other nonlinear effects in laser fusion are discussed. Dawson's contributions in the allied areas are also reviewed.

I. Introduction

In a festive and relaxed atmosphere on the island of Catalina off the coast of Los Angeles, California the International 'Dawson' Symposium on the Physics of Plasma was held during the typically southern California sunny days of September 24 and 25 of 1990. The Symposium was held on the occasion of Professor John M. Dawson's 60th birthday (Sept. 30, 1990), (actually a week earlier due to the overlapping IAEA Conference) to reflect on his trek through research and achievements that impacted the communities of plasma physics and many allied fields. Some seventy international participants from the United States, Canada, Japan, Europe, etc., including Johns' parents and Nancy's mother along with their children and their spouses, gathered at this joyful event. The scientists there were not only from academia but also from many laboratories and private industries. They were his former students, postdocs, associates, colleagues, and friends, and they still are.

The symposium was steered by the International Steering Committee listed in Table I, locally organized by the Internal Organizing Committee, and its proceedings were conducted under the stewardship of Dr. Tom Katsouleas of UCLA. Thanks to the intense and sincere effort by the organizers, the format and contents of the gathering were at the same time reflective, informative, and thought-provoking, organized in such a way to encompass a wide variety of the fields that John Dawson has pioneered and cultivated in his illustrious career.

The speakers and their topics were clumped into seven subcategories over the one and a half days. They were: (i) magnetic fusion, (ii) basic plasma physics, (ii) space physics, (iv) laser fusion, (v) isotope separation, and (vii) accelerators and light sources. The list of the speakers and their titles is given in Table II. As is obvious from the list, the far-reaching nature of topics and the caliber of the speakers illustrate the kind of science and scientists John Dawson has shared his life and ideas with. If we tried to summarize the entire session, it would take as many authors to cover them as speakers. Here we have to be content with a description of some of the highlights of the Symposium. I will like to ask leniency from the speakers whose talks I would not be able to cover because of limited space. This is not due to importance attached to the talks, but rather the judgment I made for the nature of the present journal. In particular highlighted in the following are the subjects of magnetic fusion and then those of laser fusion and related topics. In Sec. II, topics of magnetic fusion are discussed. Those of laser fusion and related areas follow in Sec. III. And finally, Sec. IV covers other allied subjects of interest.

In the final section we survey the accomplishments of John Dawson as a scientist and as a man. When it is appropriate and helps enhance the contents, my personal reminiscences are occasionally inserted.

II. Magnetic Fusion

Although I never asked explicitly, apparently, it seems that magnetic fusion was John Dawson's first (professional) love, as he went to Princeton Plasma Physics Laboratory immediately after completion of his Ph.D. dissertation on atomic physics at the University of Maryland in 1956. He quickly rose to the leadership of the Theory Division there. During his Princeton era he has made many epoch-making works, including the one-dimensional exact solution of nonlinear plasma oscillations, computer modelling of plasma kinetics, radiation from and interaction with plasma, and others.

Harold Furth of Princeton University highlighted among these the concept of "two-component" plasma reaction in the first talk of the Symposium. In 1971 Dawson along with Furth and Tenney published the idea of operating a non-Maxwellian fusion plasma.[1] This was the "eve" of the announcement of the stunning results of the Russian tokamak.[2] John Dawson realized that the most reactive particles are those of high energy and thus it is advantageous to maintain a populous concentration of energetic deuterons as much as possible by injecting a beam of deutrons at a high energy into plasma. Their calculations show that with approximately 150KeV injection energy of deuterons into as low as 4KeV plasma (electron) temperature one can reach a "scientific breakeven", i.e. the Q value, the ratio of fusion energy to the energy supply (or loss), reaching unity. Further he showed Fig. 1 (from Ref. 1), illustrating the energetically optimal operation for fusion energy multiplication (the multiplication factor $F \equiv Q$) for various electron temperatures. The graph shows the range of deuteron injection energies of $150 - 300$KeV and the maximum multiplication of $Q \sim 4$ at electron temperature $T_e \sim \infty$ (i.e. > 100KeV). Such an operation is sometimes called the wetwood burner, as opposed to the ignition, which is characterized by $Q = \infty$. Dawson continued to pursue his interest on the wetwood burner.[3,4] The condition for $Q = 1$, which imposes conditions on the plasma density and temperature through the plasma reactivity, is often called the Lawson criterion of the fusion breakeven.

Dr. Furth emphasized by showing several figures,[5] including Fig. 2, that by allowing a non-Maxwellian plasma (or plasma with a beam component) the neutron yield and thus the fusion power are greatly enhanced under given conditions. He showed in Fig. 3 that, therefore, the recent world's major experiments have been run in this mode to achieve higher fusion yield.

Bruno Coppi gave a talk on his intersection with John Dawson's work; i.e., on the possibility of advanced fuel fusion. He commented that he was not aware of John's effort in advanced fuel till the early 80's, as the comprehensive article on the subject was published in 1981.[6] While Coppi explores advanced fuel application in the second stability regime of tokamak (the higher plasma β regime),[7] Dawson was exploring plasma confinement configurations radically different from tokamaks. John explored a concept summarily called surface confinement or surmak.[8,9] This may be regarded as an outgrowth of an octupole (or multipole) concept.[10] By increasing the number of multipoles the fields increase near the magnets and decrease rapidly away from them, thereby providing a plasma nearly devoid of magnetic fields sufficiently away from the surface toward the interior. These attempts by Dawson and

Coppi are motivated to achieve high β plasmas so as to reduce the synchrotron radiation from high tempeatrue plasmas.[6,11] It is well known[6] that the cross-section of advanced fuel such as D^3He reaches its peak at much higher energies than that of DT (and typically less cross-section even then). Thus it is necessary to achieve higher plasma temperatures (and longer confinement time), leading to more radiation losses. He pursued even more aneutronic reactors of $p\,^{11}B$ fuels.[12] John thought in this connection that it is worth exploiting synchrotron radiation from the high temperature plasma to drive the magnet current.

In spite of Dr. Coppi's encounter with Dawson's effort in early '80's, John had been working on advanced fuel already for many years by then. I can testify to this, personally, since, as a newly arriving postdoc, I was assigned to work on a portion of the advanced fuel reactor research project funded by EPRI (Electric Power Research Institute, Palo Alto, CA) in early 1976. Throughout the 1970s he was actively working on so-called "alternative concepts" particularly suitable for advanced fuels. This effort during this epoch can be seen by his numerous reports.[6,8,9,12] He was also thinking about floating internal rings with small toroidal fields for advanced fuels.[13] Like his idea on beam-enhanced fusion reactivity, John wanted to explore every possible avenue to improve the attainment of fusion, in this case, by the (ion-cyclotron) wave-enhanced confinement. In his Final Report to EPRI (unpublished) he explains: *The diffusion of particles into the (mirror) loss cone can be considered... through the entropy change* $\partial S/\partial t$*, (which) is roughly related to ion-ion collision frequency. If an ion cyclotron wave is applied to push the distribution back to the loss cone, mirror losses could be reduced. The minimum amount of power required to do this is* $T_i\,\partial S/\partial t$. I was assigned to study such a prospect by computer simulation at the time and a summary may be found in Ref. 14.

I still remember John's face radiant with his heightened curiosity and excitement when he found that one of the most important fuel ingredients for advanced fuel fusion ^{3}He, which is rare in natural abundance, seemed to be found abnormally abundant in Hawaiian volcanic gases.[15] Later NASA's Apollo mission discovered that the lunar soil contains a very (abnormally) high concentration of ^{3}He on the surface ($\sim 50\,\mathrm{cm}$) that has been deposited by the solar wind.[16] This abnormally high concentration may be related to the equally abnormally high ^{3}He content in solar winds due to impulsive solar flares.[17] Kulcinski[18] argued that mining and transportation of ^{3}He to the Earth for fusion fuel still can be cost effective. It should also be noted that abnormally high isotopic concentration of ^{3}He in many commercial metals has been reported.[19]

John's curiosity knows no bounds. Even when he is thinking about a magnetic fusion reactor, his mind may wander to Hawaiian volcanoes or an x-ray bimental boiler,[6] or to the surface of the Moon. It also surprised me one day in 1976, when he was painstakingly collecting nuclear fusion rates for various elementary processes,[20,21,22] as I assumed at the time such data were well established and on top of it John did that chore.

III. Laser Fusion

As early as 1963 (published in 1964)[23] just a few years after the first laser was constructed and immediately after Basov and Krokhin,[24] John Dawson suggested the creation of a thermonuclear fusion plasma driven by lasers. He has often come back to the topic, including Refs. 25 and 26. Appropriate to his pioneering work, foresight, and interest, several speakers talked about topics of related interest.

W. Kruer discussed generation of suprathermal electrons as a result of the resonant laser-plasma interaction, and nonlinear behavior of ion waves. The hot electron production leads to preheating of the target, thus making it more difficult to compress for thermonuclear conditions. In a short pulse irradiation of an exploding pusher target (i.e. the pulse duration less than 100 ps) the electromagnetic fields of the laser cause a strong enough ponderomotive force on the plasma, thus creating a steep density profile, at the middle of which the density n of the plasma becomes equal to the critical density n_c ($n = n_c \equiv m\omega^2/4\pi e^2$. where

ω is the laser frequency). At this resonant point in space, strong laser light absorption takes place, yielding a heated plasma (see Fig. 4, also Ref. 27). On the other hand, in a long pulse irradiation of an ablatively-driven compression, there appears a large skirt of an underdense plasma, in which the laser-plasma interaction gives rise to a variety of plasma parametric instabilities. In these large underdense plasmas the stimulated Raman instability produces hot electrons with a modest bulk temperature. The amount of the hot electron fraction correlates with Raman scattering is shown in Fig. 5 (Ref. 27). In these plasmas the reflectivity due to stimulated Raman process can be greater than 10% (see Fig. 6 and also Ref. 27).

Kruer went on to explain the second topic of laser-plasma interaction through nonlinear ion waves.[28] Kruer and Dawson, along with Rosen, showed[28] that when the beat of two electromagnetic waves equals the ion wave frequency, ion waves are nonlinearly driven and can play an important role in the laser-plasma interaction. In particular, the ion nonlinearity tends to saturate the growth of the ion density perturbation δn around 4% of the total density n_0, regardless of the intensity of the laser above a certain threshold. The experiment by Pawley *et al.*[29] and computer simulations (Kruer) both agree reasonably well, as shown in Fig. 7, but the value of $\delta n/n$ can reach as large as 0.3.

Both Lindl and Kindel in their talks touched upon the topic of laser fusion and laser-plasma interaction. K. Nishikawa in his talk discussed the high frequency conductivity of a plasma due to Dawson and Oberman[25] and related to the parametric instabilities[30] and anomalous absorption. The talk by P.K. Kaw was about driving current by the ponderomotive force of the electromagnetic waves.

In addition to the microimplosion of the fusion fuel by lasers discussed above, Dawson thought about utilization of intense lasers in initiating fusion reactions in less densities. In the paper[31] he introduced a simplest possible magnetic confinement system, a long solenoid plasma, heated by (a) laser beam(s), whose length is over a kilometer for the end loss confinement time requirement (Lawson criterion). In spite of its length it has several advantages, including guaranteed plasma stability, simple reactor configuration, etc. Its length is no more than the SLAC linear accelerator and far smaller than the SSC (superconducting super collider), only except for its utility. In fact, a hundred GWatt reactors can be placed at each corner of the SSC, were it a ring of the long solenoid reactors.

It so happened that when I was a graduate student my Ph.D. advisor, Professor Norman Rostoker, suggested that I consider as my thesis topic heating methods (by lasers or electron beams) of the plasma in Dawson's long solenoid reactor. As discussed by Kruer and others, the long-pulsed laser irradiation of plasmas induces the stimulated scattering, a highly nonlinear process. The heating by electron beams turns out to be again highly nonlinear. It may have been fate that while working on Dawson's reactor concept, I felt the limited power of the traditional analytical approach for highly nonlinear plasma problems and was compelled to believe the only way was the computer simulation approach, which once again Dawson championed. I somehow or naturally ended up as his postdoc.

IV. Allied Fields of Science and Technology

John Dawson's contributions to science and technology go far beyond those on magnetic and laser fusion. On one hand his adventures are intimately related to the fusion research, either for the purpose of making fusion work or as a spinoff of fusion research. On the other hand, they are due to his adventurous, pioneering spirit which knows no boundary of disciplines. He often finds himself exploring new ideas in an entirely new field he boldly created a moment ago.

One of his most famous contributions in the method of plasma physics is his pioneering effort in the particle approach of plasma simulation.[31,32] It is in this endeavor that he interacted with perhaps a greatest number of younger scientists, including J. Boris, W. Kruer, J. Lindl, A.B. Langdon, H. Okuda, A.T. Lin T. Kamimura, V. Decyk, J.N. Leboeuf, and myself. It was the vintage Dawson who started this endeavor, as he foresaw the tremendous growth of the computer and the very complex and nonlinear nature of plasma physics. Reflecting on his contributions in the field, the speakers discussed the subject with Sudan on the subgrid modelling and Decyk on the future directions of simulation. Besides these talks, others such as Kruer, Kindel, Bingham, Lindl, and Johntson talked about the various physics based on the simulational approach.

John was always interested in concrete applications of science and technology for the betterment of humankind. One of his many inventions was his isotope separation process[33] that was discussed by Chen and by one of the banquet speakers Dr. Maniscalo of TRW. His method of preferential spin-up of the desired isotopic element and the associated large body of techniques has been implemented and perfected at TRW. One such technique is the coil configuration called the Nagoya type III, which John encountered in Nagoya's Institute of Plasma Physics on one of his many trips to Japan and was later analyzed in detail.[34] This is a coil configuration that is effective in penetrating rf electric fields into the plasma. This may represent a good example of one idea coming to fruition on a different tree; i.e., in a different country. Of course, John has brought a large number of his own ideas across the Pacific, shaping some of IPP's programs and other Japanese fusion/plasma programs, as Prof. Husimi, the first director of IPP, testified. The TRW's capability of separating the isotope of ^{102}Pd turned out to be crucial in destroying malignant cancer cells of the prostate, as the Dawson method is inexpensive in collecting a significant amount of rare elements.

Another allied area which John has been interested for many decades is particle accelerators and radiation sources, or to put it another way, the interaction of radiation and plasmas. Although his interest in this field is deep rooted from earlier years,[35] the topic is presently quite hot and many lively talks have been devoted to this. Namely, T. Johnston and R. Bingham talked about the laser beat/wake acceleration of electrons[36] and subsequent developments, and C. Joshi talked about the latest development in photon frequency up-conversion in a plasma.[37] Tudor Johnston during his talk dedicated a very fitting poem to John:

A plasma magician named Dawson
Is fertile with ideas that blossom,
    Though his concepts are wild,
    Each latest brainchild
Is backed by code runs that are awesome!

Breaking waves he found was so fine,
Near a surf beach he never would pine.
    "Surf's up in the hypercube,
    Comes John in a supertube.
Riding waves till the end of the line!"

Catalina's the place to say, "John,
Though phase space is maybe a con,
    And flows and vortexes
    Just sent to perplex us,
May you always find waves to ride on!"

V. Dawson as Scientist and Man

A great scientist, as John Dawson surely is, teaches more by example than in any other way. While students, postdocs, and colleagues work with a great man, they have intimate opportunities to learn just what his style of working is, and can make educated guesses at some of the secrets of his success, as when papers are published and lectures are given, however, they are too profound, too organized, and too remote. And only a glimpse into his inner working and feeling to be able to emulate his style can be obtained in the informal.

private hours given a student. Perhaps one of the main purposes the present article can serve is to shed light on such intimacy so that some of the experiences with John Dawson may be shared with the reader, as I was privileged to share some of the most eventful five years of my career. John, the great thinker, has many outstanding traits we underlings can learn. Instead of listing all these traits, I would like to mention a couple of occasions for illustration.

It was probably the Summer of 1977 when Charlie Kennel, from our department at UCLA, just returned from a trip to Russia. Charlie entered excitedly into Dawson's office with his typical contagious enthusiasm, saying that he witnessed a wonderful simulation experiment[38] of a magnetosphere by Podgorny of Moscow. It was a crude experiment with temperatures, densities etc., different from the real magnetosphere, but showed a global magnetic field structure and magnetic activities. When Charlie reported his findings on the experiments, in the office were Dawson, Leboeuf, and myself, discussing the computer code development called magnetohydrodynamic (MHD) particle code, John's invention to extend particle simulation method to MHD.[39] As a young and still brash scientist, I remember I said something like *Oh, it is easy for our code to simulate such.* Such a statement can be made when a young scientist knows nothing of what others have done; otherwise, he would be afraid that such a simple thought would be too simplistic or, worse, wrong. As a result, one tries to hold back, thinking something does not fit, or someone must have done it, etc. Now, Dawson is not like that. One may say that he is a rah-rah guy, or more accurately, loves new things and is not afraid of what others might think or might not think. He immediately got excited at the prospect of doing (probably the first — we did not know but it turned out to be that way) global MHD simulation of the magnetosphere. So we did just that.[40] Lesser visionaries may have argued that we didn't have enough resolution, not large enough magnetic Reynolds number etc., so it was not worth the effort. Quite the contrary. John is the guy, himself, who was excited by the idea, just like a child gets excited by his own little thought, pursuing it till resolution. If I am not mistaken, this was John's first serious engagement with space physics research. In the Symposium, Bob Bingham elaborated more on simulations of space plasmas.

The second example is more personal. It must have been a day in May, 1976 just several months after I graduated and took a position at UCLA under John when he came back ill from the Anomalous Absorption Conference held in Canada. It so turned out that his illness was due to malignancy. He went through immediate surgery followed by many months (years) of intense chemotherapy. The medicines must have been extremely strong, as right after prescription of the drugs he invariably became very sick and lost most of his blonde hair. What was most awesome and inspirational to me was his courageous attitude. Upon the major life-threatening illness and this equally severe medication he never stopped working on physics! John used to be a chubby man, but after the surgery and medication he became quite thin. When he was too sick to come to the office, we were summoned to his Pacific Palisades home to discuss our results. Without fail, he fully discussed the subject at hand when I visited him. A more surprising thing was that he was even more creative, or at least it seemed to me, during this serious period than the previous time. Charlie Kennel jokingly said that because he was free from all the daily chores, he was more creative. Charlie was right. During this period he worked on advanced fuel fusion, various ideas on fusion reactors, MHD particle codes, isotope separation, free electron lasers, initiation of space plasma simulation. and laser acceleration, among other topics, in addition to more "mundane" duties of teaching students. This, I believe, more than anything else is the testimony of what kind of man John Dawson is.

Nancy Dawson made an emotional speech at the banquet after Dr. Maniscalo of TRW on his contribution of isotope separation, which produced the ^{102}Pd isotope used to help therapy of prostate cancer. This was such an ironical coincidence that John's inspiration and handiwork while fighting his own cancer helped many patients of cancer by his invention.

Acknowledgment

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Table I

International Steering Committee

B. Bingham
B. Coppi
B. Cohen
P. Drake
R. Gould
W. Horton
T. Kamimura
T. Katsouleas
P. Kaw
J. Kindel
W. Kruer
R. Kulsrud
A.B. Langdon
J.N. Leboeuf
J. Lominadze
C.S. Liu
J. Nuckolls
R.S. Pease
A. Sessler
P. Staudhammer
R. Sudan
H. Wilhelmsson

Internal Organizing Committee

M. Abdalla
F.F. Chen
R.W. Conn
V.K. Decyk
J. Foster
B.D. Fried
C. Joshi
C.F. Kennel
W.B. Mori
C. Pellegrini
R. Peccei

Table II

International 'Dawson' Symposium on the Physics of Plasmas

Hosted by: Institute of Plasma and Fusion Research at UCLA, UCLA Physics Department, TRW, and the Plasma Physics Research Institute at LLNL.

Monday, September 24

Session O — Welcoming Remarks
Tom Katsouleas, Symposium Chairman
Raymond Orbach, Provost, UCLA

Session I — Magnetic Fusion
(session chair — B. Coppi)
H. Furth (PPPL) — "Non-Maxwellian Fusion Plasmas and Other Curiosities"
B. Coppi — "Magnetic Fusion"

Session II — Basic Plasma Physics (I)
(session chair — W. Horton
P.K. Kaw (IPR, Bhat, India) — "AC Helicity Injection: Current Drive in Tokamaks Using Ponderomotive Forces"
R. Sudan (Cornell) — "Sub-Grid Modelling in MHD Numerical Simulations"
C. Oberman (PPPL) — "Atoms in Intense Electromagnetic Fields"

Session III — Basic Plasma Physics (II)
(session chair — W. Horton)
K. Nishikawa (Hiroshima Univ.) — "Dawson-Oberman Formula for Hi-Frequency Conductivity and Anomalous Absorption of Intense Electromagnetic Fields"
K. Husimi (Prof. Emeritus, Univ. Nagoya & Univ. Osaka) — "Early Days of Institute of Plasma Physics in Nagoya and Professor Dawson"
J. Kindel (LANL) — "Very Short Pulse Laser-Plasma Interactions"

Session IV — Space & Astrophysical Plasmas
(session chair — T. Birmingham)
R. Bingham (RAL) — "Simulation of Space Plasmas"

Tuesday, September 25

Session V — Inertial Fusion
(session chair — T. Johnson)
W. Kruer (LLNL) — "Supra-Thermal Particles and Other Plasma Effects in Laser Fusion"
J. Lindl (LLNL) — "Progress on Ignition Physics for ICF and Plans for a Nova Upgrade to Demonstrate Ignition and Propagating Burn by the Year 2000"

Session VI — Dawson Isotope Separation Process
(session chair — J. Maniscalco)
F. Chen (UCLA) — "Double Helix: The Dawson Isotope Separation Process"

Session VII — Computer Simulation
(session chair — O. Buneman)

B. Langdon (LLNL) — "30+ Years of Plasma Simulation" (given Sept. 24 afternoon)
V. Decyk (UCLA) — "Future Directions in Simulation

Session VIII — Accelerators & Light Sources
B. Bingham (RAL) — "Plasma Accelerators"
T. Johnston (INRS) "Beatwave Acceleration — Recent Fluid Simulations"
C. Joshi (UCLA) — "Frequency Up-Conversion of Radiation Using Plasma Techniques"

Figure Captions

1. Energy multiplication factor $F(\equiv Q)$ as a function of deuteron injection energy W_0 for various electron temperatures of cold-triton-target plasma, assuming total energy release of 22.4MeV (from Ref. 1).

2. Fraction of total neutron rate as a function of neutral beam injection power, showing the "two-component" idea of enhanced fusion reactivity (from Ref. 5).

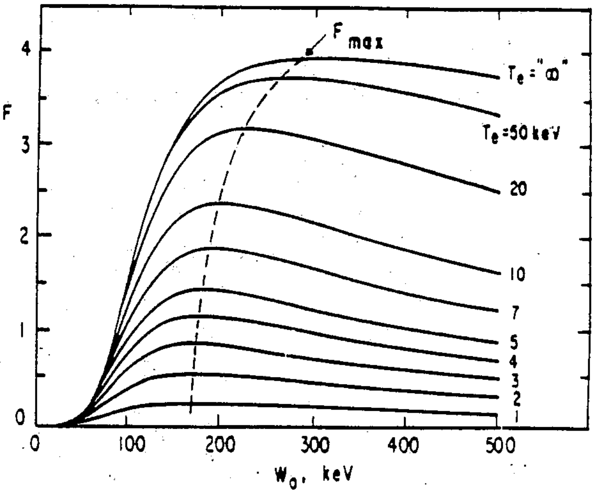
3. Progress in magnetic fusion power in recent tokamaks (from Ref. 5).

4. Superthermal electron generation in short scalelength laser plasma interaction. The electron distribution function. The density modification is important for resonance absorption and suprathermal electron formation (from Ref. 27).

5. Electron heating in longer scalelength laser (underdense) plasma interaction. Heating of the underdense plasma happens due to the Raman instability. (a) The electron distribution function. (b) The hot electron fraction of the irradiated plasma vs. the Raman scattered light fraction, indicating the Raman instability nature of the plasma heating in this case. The target Au disk with $0.53\,\mu m$ Novette experiments 0.5-4kJ, 1ns pulses at $10^{14} - 2 \times 10^{16} W/\mathrm{cm}^2$ power density (from Ref. 27).

6. The Raman scattered light fraction vs. the density scalelength of the plasma L (normalized to the laser wavelength λ). The stimulated Raman reflectivities greater than 10% have been observed in large scale plasma irradiation in accordance with theoretical and computational expectation (a detrimental effect that should be avoided for laser fusion) (from Ref. 27).

7. The ion wave density fluctuations driven by beat of lasers. The saturation is due to ion nonlinearity, as explained by Dawson and Kruer. The ratio of the second harmonic fluctuation divided by the fundamental as a function of the geometrical mean of two laser powers. Experiments by Pawley *et al.* and particle simulation are compared favorably (from Ref. 27).



F
0
1
2
3
4
0
100
200
300
400
500
W_0, keV
F_{max}
T_e = "∞"
T_e = 50 keV
20
10
7
5
4
3
2
1

Fig. 1

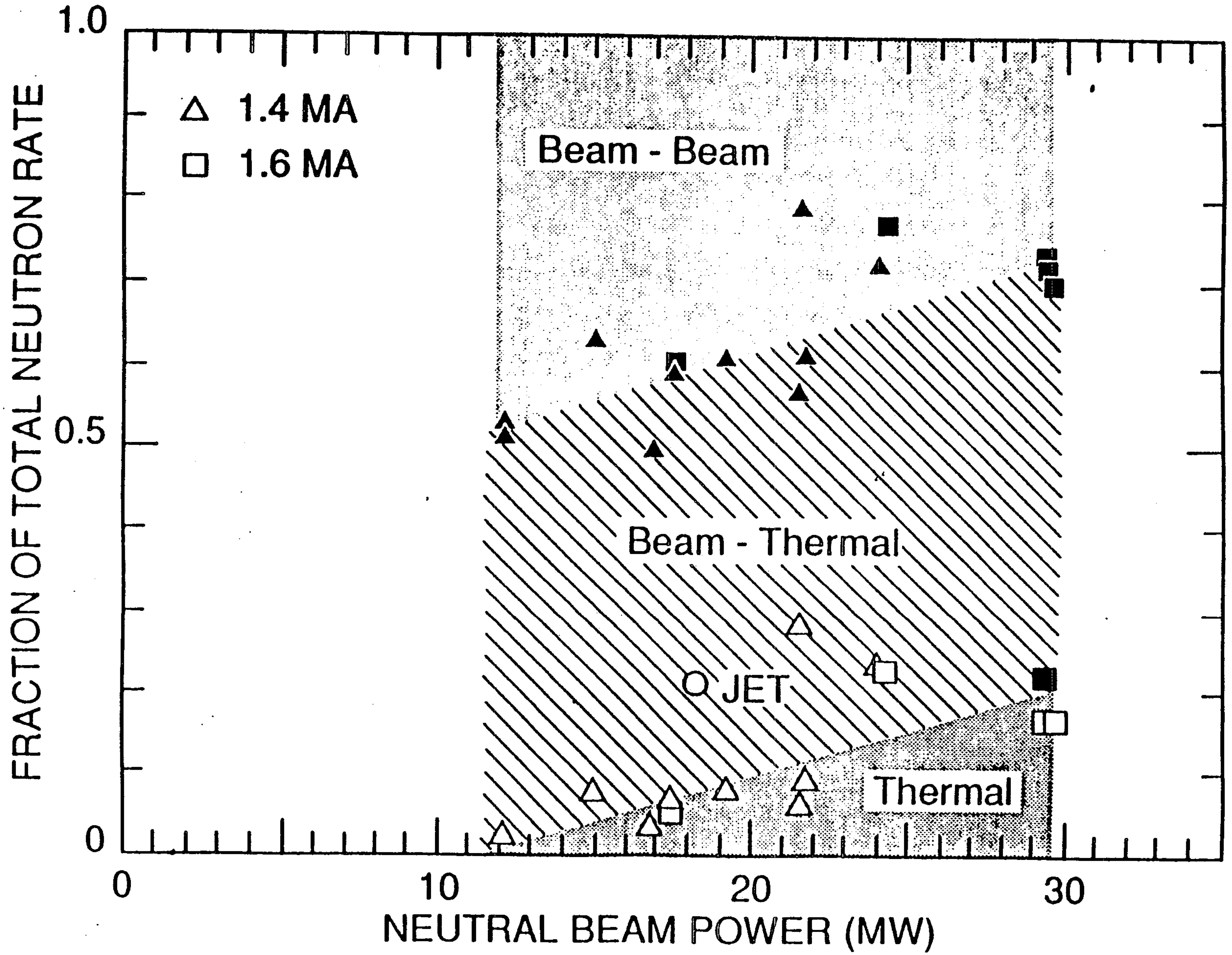

1.0
0.5
0
FRACTION OF TOTAL NEUTRON RATE
0
10
20
30
NEUTRAL BEAM POWER (MW)
△ 1.4 MA
□ 1.6 MA
Beam - Beam
Beam - Thermal
Thermal
○ JET

Fig. 2

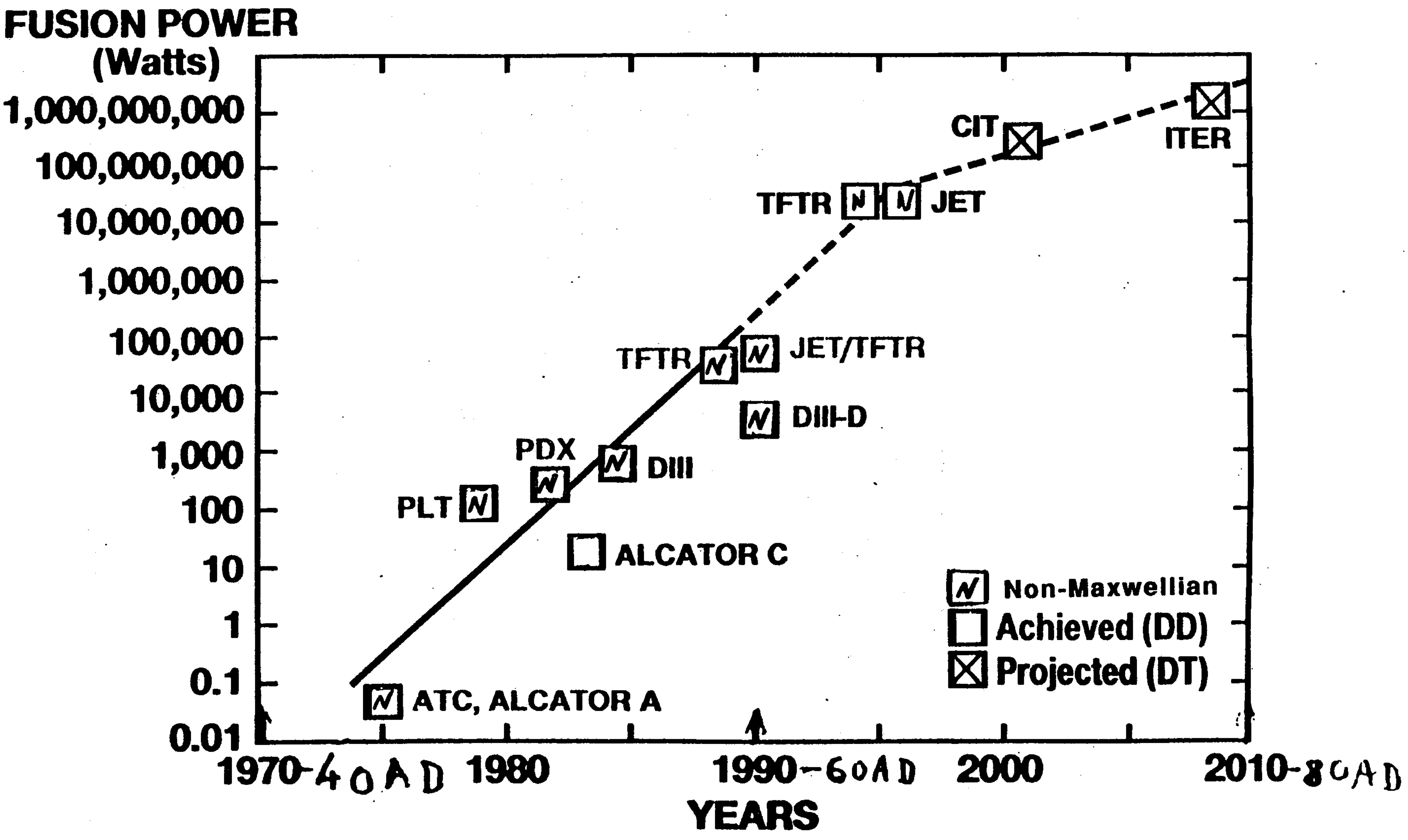

FUSION POWER
(Watts)
1,000,000,000
100,000,000
10,000,000
1,000,000
100,000
10,000
1,000
100
10
1
0.1
0.01
1970-40 AD
1980
1990-60 AD
2000
2010-80 AD
YEARS
CIT
ITER
TFTR
JET
TFTR
JET/TFTR
DIII-D
PDX
DIII
PLT
ALCATOR C
ATC, ALCATOR A
Non-Maxwellian
Achieved (DD)
Projected (DT)

Fig. 3

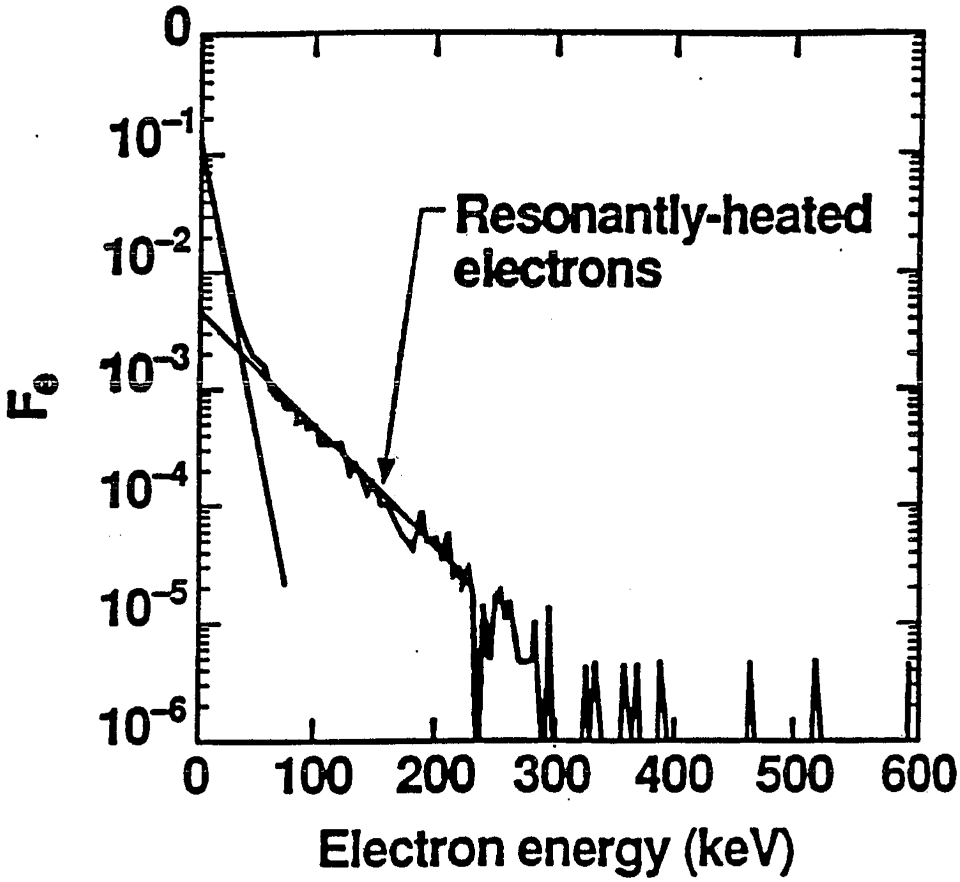

0
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
Fe
0
100
200
300
400
500
600
Electron energy (keV)
Resonantly-heated electrons

Fig. 4

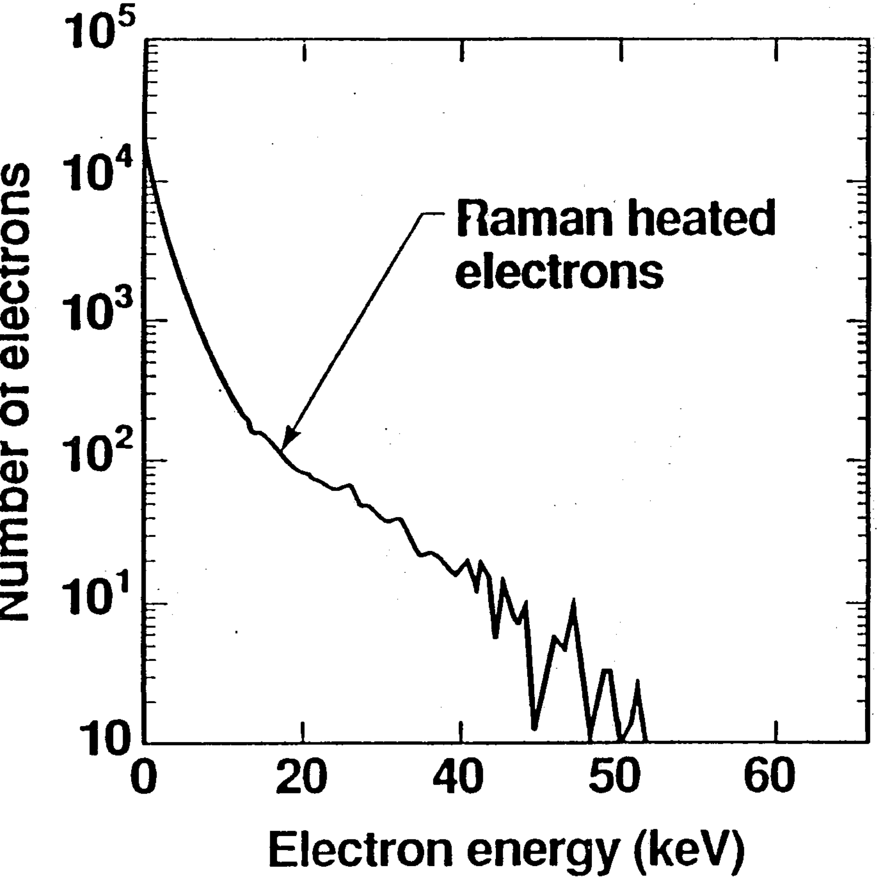

Number of electrons
10
10^1
10^2
10^3
10^4
10^5
0
20
40
50
60
Electron energy (keV)
Raman heated electrons

Fig. 5a

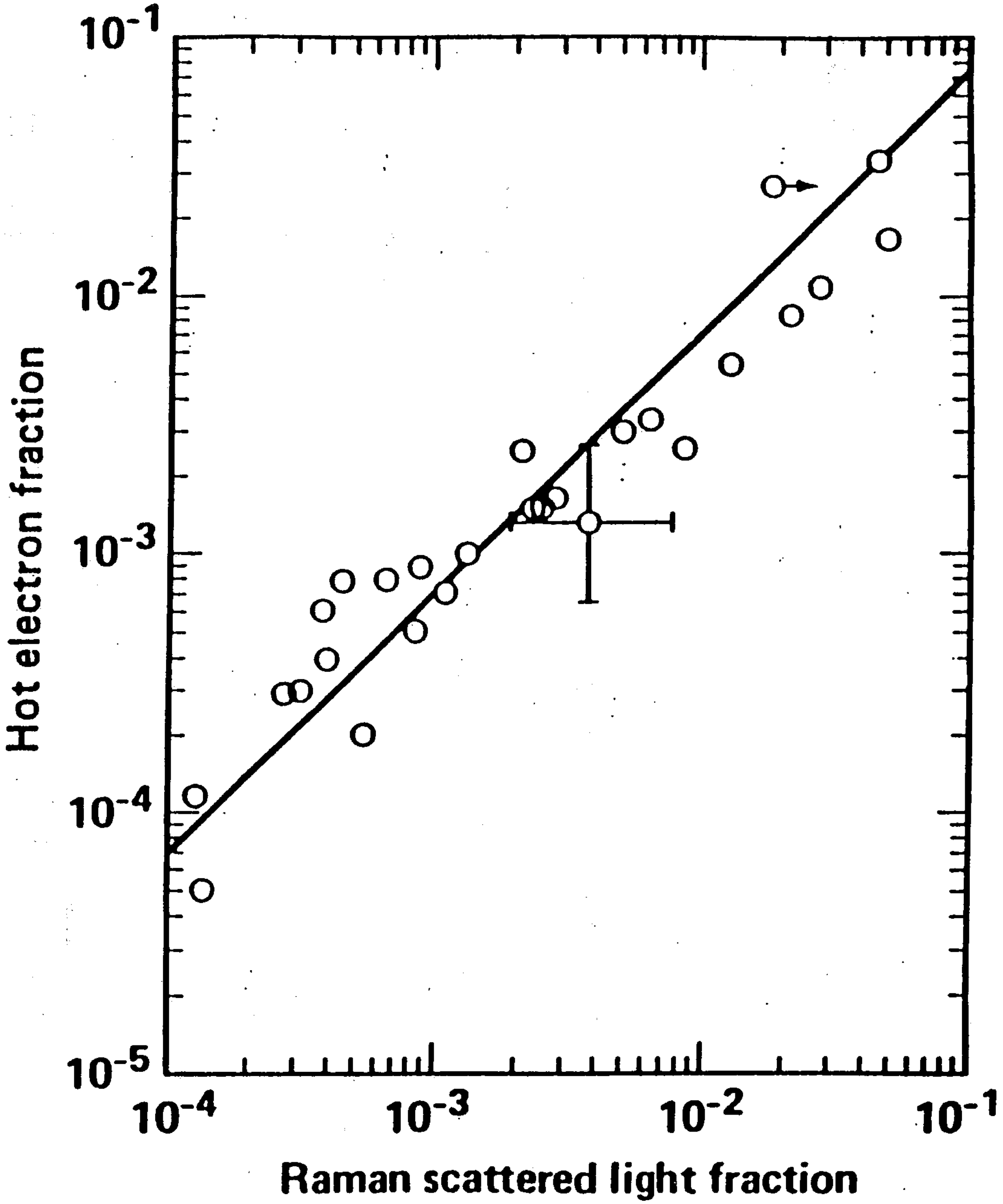
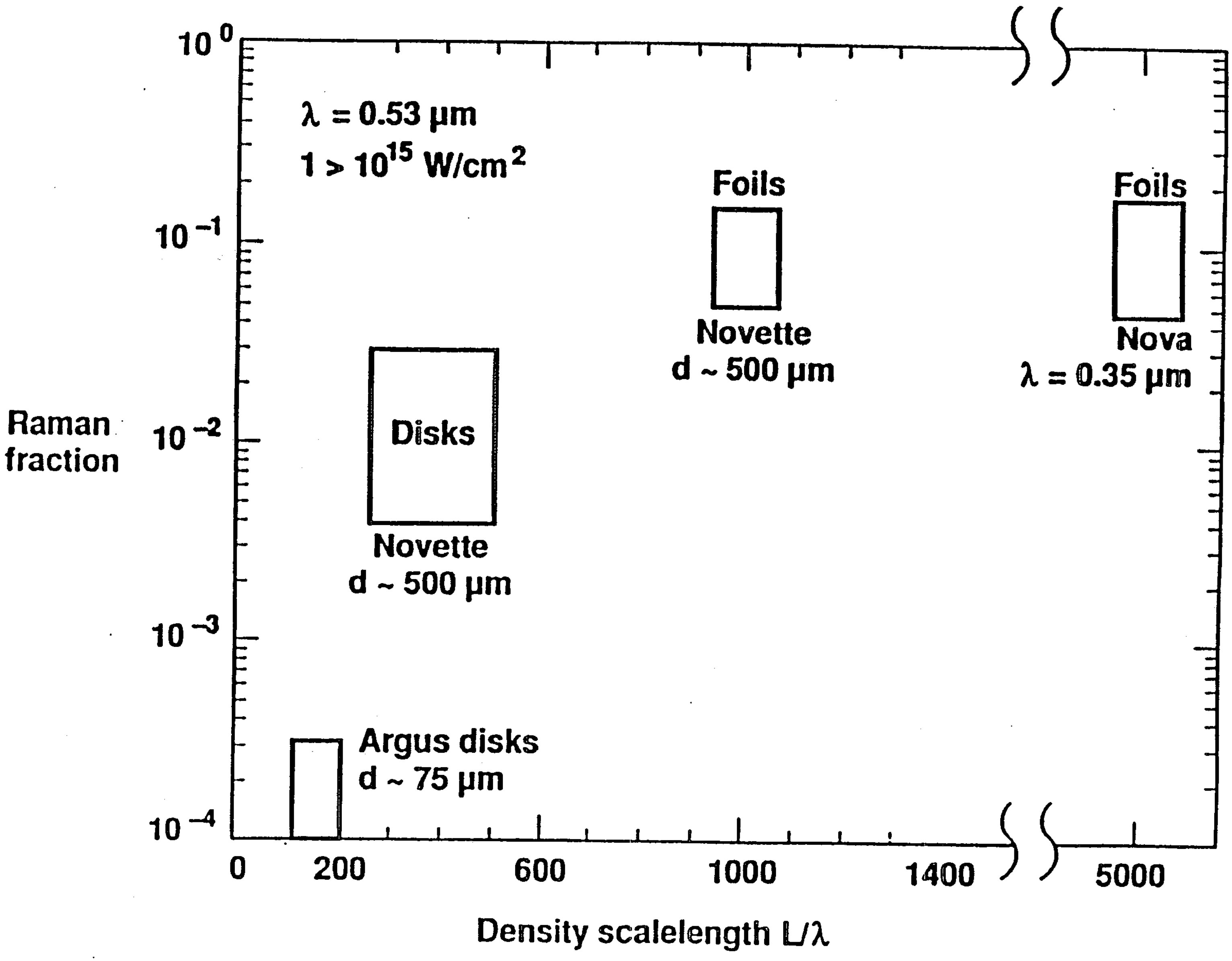

Hot electron fraction
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Raman scattered light fraction
10^{-4}
10^{-3}
10^{-2}
10^{-1}

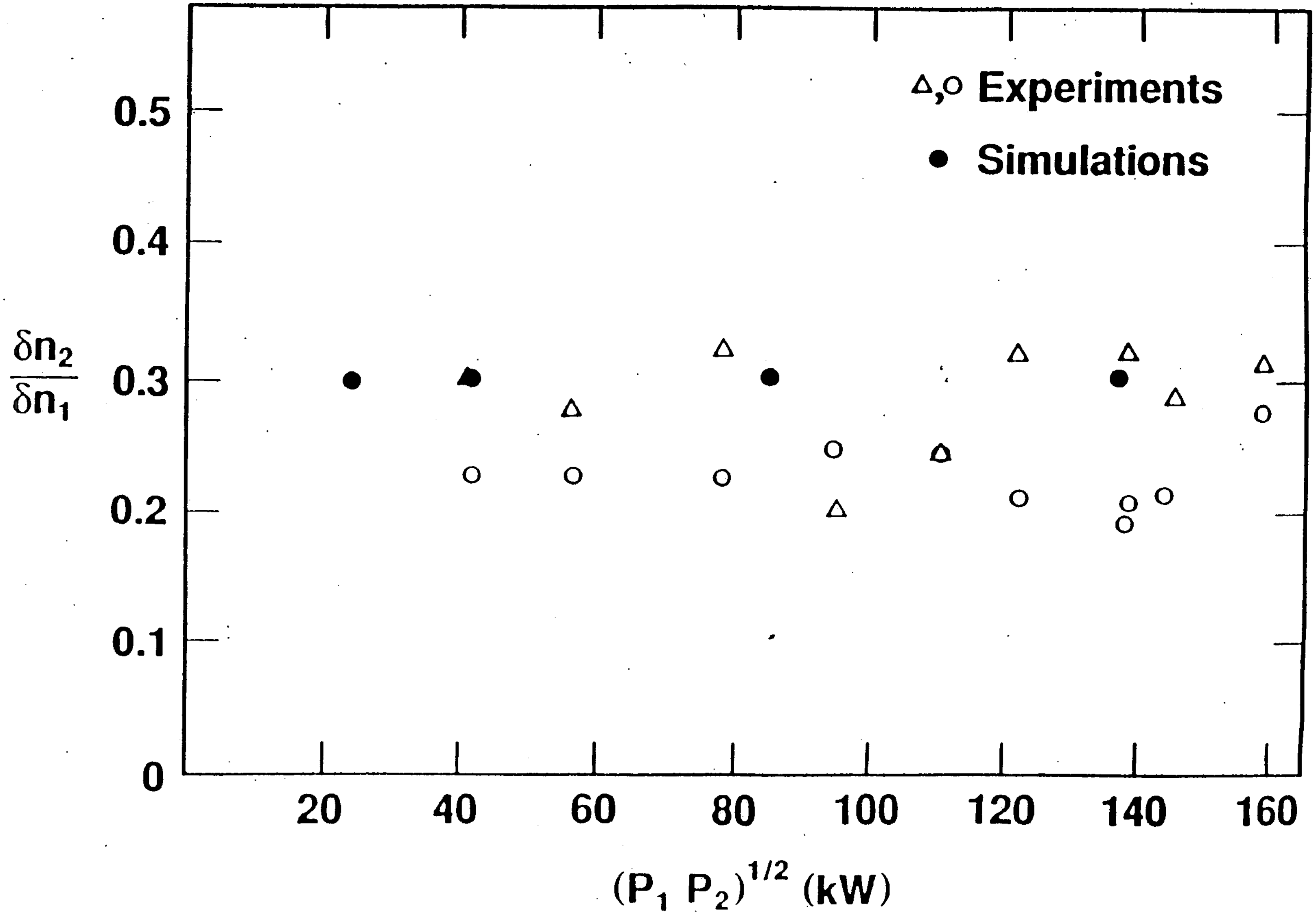
Fig. 5b



$\frac{L}{\lambda} \sim 5000$ regime

Darrow et al. (1989)

Fig. 6



0.5
0.4
0.3
0.2
0.1
0
$\frac{\delta n_2}{\delta n_1}$
20
40
60
80
100
120
140
160
$(P_1 P_2)^{1/2}$ (kW)
△,○ Experiments
● Simulations

Fig. 7