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FINAL REPORT OF PROJECT CHALICE

EXPERIMENTAL INVESTIGATION OF CUSPED CONTAINMENT GEOMETRIES
CHALICE

ATOMIC ENERGY COMMISSION
CONTRACT NO. AT(11-1)-2320

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FINAL REPORT OF PROJECT CHALICE

Prefatory Remarks

This final report on Project Chalice is an updated version of the "Historical Survey of Project Chalice" which was published in 1967. The project was terminated in 1971, and the final version presented here is tempered by the passage of time. The lessons learned in this project are summarized at the very end.

I. Introduction

The history of Project Chalice is to be found in our voluminous annual reports. Most of our efforts in the early years went into "engineering and development" of components. In the latter part of the project the direction shifted into diagnostics. At the termination of the contract, the overwhelming thrust was to develop more sophisticated diagnostic techniques capable of analyzing the complex time development of the plasma which prevailed in the Chalice experiment.

Looking backward, the entire system really was a complex experiment in plasma dynamics. In the period 1960-70, it was perhaps the most complex plasma effort in existence.

Because of this complexity the system we built had to be versatile, capable, and we are convinced, if adequately funded, would have been highly successful. Any complex experiment such as Project Chalice has three basic ingredients. First, actual engineering of the system; second, the diagnostic tools needed for analysis of the experiment; and finally, the quality of the physics brought to bear in the analysis of the plasma dynamics. A thorough job on all three phases really required a large amount of capable, devoted manpower.

Project Chalice successfully tackled all three phases. . We pioneered in the design of capacitors, transmission lines, and high powered switches needed for very fast compression of plasmas. In diagnostics, we successfully used Thomson scattering for measuring the temperature of the plasma.

Moreover new techniques were discovered and proposed for a deeper analysis of plasmas. Finally, a series of original papers on the theory of plasma dynamics were published. A brief summary of all three aspects are herein presented.

II. Original Chalice Proposal

The original Chalice scheme is due to Finkelstein, Koslov, Rogers and Schmidt and was presented at the 1959 meeting of the Division of Plasma Physical Society of A. P. S. Historically, even earlier, Dr. Keith Boyer^{*} in Los Alamos had in 1958 assembled design studies and equipment for the purpose of experimenting with two θ -pinches and a cusp. These were unfortunately abandoned for other experiments.

The original Chalice proposal is shown in Fig. (1). In principle, the sequence of operations are four in number, simple to describe, but quite difficult to carry out in reality. (See Fig. (1)).

- A) Cold plasma is formed inside two coils by rf preionization.
- B) Two θ -pinches are then produced by a fast bank. The currents in the coils are in opposite directions. The effect of the θ -pinches is to generate two hot dense plasma threads. At peak magnetic fields the currents in the coils are crowbarred.
- C) By making use of high resistance material for the inside mirrors; the inside mirrors vanish, thereby allowing the plasma threads to be injected into the cusp. Work on the

^{*} Private Communication.

Figure -1-

ORIGINAL CHALICE PROPOSAL

plasma is accomplished by virtue of the piston-like action of the magnetic field. The threads thermalize in the cusp by interaction.

- D) Plasma is confined in the cusp by the crowbarred current.

III. Final Scheme of Chalice

The final embodiment of Project Chalice is shown schematically in Fig. (2).

- A) Instead of rf which we found to be too weak, a linear discharge of a 7.5 μ f capacitor preionizes the gas to around 1 ev. temperature.
- B) Prior to the firing of the θ -pinch bank, a slow "heavy" cusp-bank is switched on. This appears to have little noticeable effect on the plasma. The reason for a special cusp bank is as follows. A fast θ -pinch bank when crowbarred has only a short crow-barred life-time. Hence, the plasma confinement would necessarily be short. Therefore, we were driven to drop the idea of using the θ -pinch coils for long-time confinement in the cusp region. Instead special cusp coils were fabricated whose primary function is to confine the plasma in the cusp region.

Now the question arises, why switch the cusp-coils on first, prior to the θ -pinch coils? The answer is that by suitable timing of cusp bank with the θ -pinch bank, we can generate

FIGURE -2-
SCHEMATIC DIAGRAM
OF PROJECT CHALICE

dynamic magnetic mirrors. (The actual sequence of events is quite complicated and presented in detail in the Annual Reports.)

- C) Approximately 3 or 4 microseconds after the cusp bank commences, (cusp bank has a period of around 36 microseconds), the θ -pinch bank is switched on. This bank is very fast (See Table I), and indeed, a great part of Chalice history pertains to the construction of this bank. Two fast θ -pinches are generated, producing dense hot plasma. In the initial phases of the pinch the dynamic mirror is formed by combination of θ -pinch and cusp fields in the plane of the cusp coil.

The rising magnetic of the θ -pinch region into the cusp domain. The shock produced by the strong outside permanent mirrors of the system (See Fig. (2)) acts as a piston.

- D) The plasma now in the cusp region is confined by the strong magnetic fields of the cusp. The θ -pinch bank prevails only for three microseconds or so. The cusp-bank is crowbarred at the peak cusp field by a battery of ignitrons and confinement by the cusp magnetic field obtains.

TABLE I

Summary of Chalice System

(Single Channel Switch per Quarter Coil)

Preheater

Capacitance	7.5 μ farad
Inductance	750 nanohenries
Period	15 microseconds
Operating Voltage	7.5 kilovolts
Estimated Max. Operating Voltage (Ringing)	10 kilovolts
Maximum Magnetic Field (B_0)	4 kilogauss
Estimated Pinch Radius (From STL Data)	.25 inches
Mode of Firing	Spark Gap

Cusp Bank

Capacitance	135 μ farads
Inductance (Shorted)	25 nanohenries
Ringing Frequency (Shorted)	100 kilocycles
Period (Shorted)	10 microseconds
Total Period with Load	35 microseconds
Operating Voltage	10 kilovolts
Estimated Max. Operating Voltage	15-20 kilovolts
Thickness of Cusp Coils	0.20 inches
Diameter of Cusp Voils	2 inches
Separation of Cusp Coils	0.9 inches

Maximum Magnetic Field in Equatorial Plane (10 kilovolts)	54 kilogauss
Position of Maximum Magnetic Field in Equatorial Plane	at coil radius
Maximum Magnetic Field on Center Line (10 kilovolts)	26 kilogauss
Inductance of Cusp Coils	150 nanohenries
Mean Coupling Coefficient to Fast Bank	0.5
Maximum Current (10 kilovolts)	230 kiloamperes
Mode of Firing	spark gap
Crow-Bar Decay Time (T_e)	60 μ seconds

Fast Bank

Capacitance	64 μ farads
Inductance of Shorted Bank (1/2 Bank)	2.4 nanohenries
Ring Frequency (1/2 Bank)	570 kilocycles
Present Operating Voltage	15 kilovolts
Estimated Max. Operating Voltage (with existing coils)	30 kilovolts
Diameter of Coils	2 inches
Inductance of Straight Coils	22 nanohenries
Inductance of Mirror Coils	24 nanohenries
Mean Coupling Coefficient between Mirror and Straight Coils	0.27
Geometric Mirror Ratio	3.4
Experimental Mirror Ratio (Center Line)	1.9
Thickness of Coils	.55 inches

Magnetic Field in Center of Mirror Coil (15 kilovolts)	30 kilogauss
Magnetic Field in Straight Coil (15 kilovolts)	32 kilogauss
Maximum Current at 14 kilovolts	270 kiloamperes
Mode of Firing	Solid Dielectric Switching
Rise Time for Entire System	1.1 μ seconds

Vacuum System

Background Pressure	5×10^{-7} mm Hg
Gas Utilized	Deuterium
Purification	Palladium Leak

IV. Ring Chalice

We should like to discuss briefly, Ring Chalice, which was proposed in 1963. Ring Chalice, we feel, has considerable merit and should be carried out experimentally.

Fig. (3) shows the original Ring Chalice scheme. It follows the major steps outlined in Section II except for an important difference. The fear was that plasma injected into the cusp would "splatter" quickly outward along the line escape and we would be left holding an empty "bag". To counteract this, plasma is formed in the doughnut region again by virtue of the actions of a fast θ -pinch bank, and then with the aid of high resistance materials, a vanishing mirror is formed and implosion of the plasma along the escape line of the cusp takes place, thereby preventing loss of plasma from the two θ -pinch injections. Crowbarring would then follow for long time confinement in the cusp.

By suitably shaping the coils in the doughnut region, one can form either a mirror arrangement or minimum B-configuration as first discussed by Furth. Clearly the scheme shown in Fig. (3) is outdated by virtue of the experience acquired in the construction of the present Chalice system (Fig. (3)). We have shown in Fig. (4) a cross section of an improved version of Ring Chalice. Here we embody a cusp coil into the system in order (a) to generate a very long confinement time which a θ -pinch bank cannot do, and (b) also produce a dynamically vanishing mirror.

FIG. -3-
SCHEMATIC DIAGRAM OF RING CHALICE

Fig. -4-
Contour Shape of Improved
Ring Chalice

Again the sequence of operations would be similar to that outlined in Section III. It is important to keep in mind that the doughnut is not to be used for the long-time confinement of plasma, inasmuch as the field lines are curved toward the plasma and presumeably would give rise to instabilities if the density were high and the time were available for the instabilities to develop.

V. Experimental Results

The principal experimental results are detailed in our annual reports and presented at numerous Physical Society Meetings and Plasma Conferences. In our early experiments we did streak and frame studies of plasma behavior both in the cusp and in the θ -pinch, sideways and end-on. We observed the "plasma bounce" wherein the two plasma fronts generated by the θ -pinches do not interact in the equatorial plane of the cusp. This occurs if the magnetic fields are not too great. The basic reason for this is that opposite currents in the two fronts repel each other. In fact if the θ -pinch bank rings, we have observed that the fronts oscillate with the ringing of the bank.

Beautiful end-in frames of the θ -pinch were taken, magneto-hydrodynamic oscillations of the θ -pinch observed and the velocities of radial instabilities measured.

In addition to this, experiments utilizing a spectroscopic streak were carried out (See Chalice Annual Report of 1965-66) wherein the degree and types of impurity generated by the plasma were measured.

It was found that as long as the linear pinch was not allowed to reach the glass walls, negligible impurity production prevailed. Furthermore, the cusp bank did not generate any noticeable impurities. These are the reasons why the strategy was adopted to switch the θ -pinch bank immediately prior to hitting the glass walls in our latest series of experiments.

Still another type of experiment carried out was the measurement (Chalice Annual Report of 1966-67) of the ratio of line intensities $H\alpha/H\beta$. This was intended for the preheater alone. This method is not too satisfactory, because of the large uncertainties involved. The solid angles are such, and the diminution by filters, beam splitter, etc. so great that considerable skill must prevail to obtain meaningful data. From the intensity ratios of $H\alpha/H\beta$, we measure a lower bound for the preheater plasma of one half electron volt. How much higher it is, we do not know. For the measurement of the intensity ratio of $H\alpha$ to the 100 Å width of the continuum at the $H\alpha$ line, we have found it to be inordinately difficult. Recently we have devised a new scheme to make this measurement simple. Such a measurement will allow us to measure by optical means temperatures up to 15 ev.

The results obtained by Thomson scattering along with a summary of the advanced diagnostic tools developed by Project Chalice are given in the next section which is a summary presented at the Fourth Symposium on Engineering Problems of Fusion Research, Naval Research Laboratory, Washington, D. C., April 20-23, 1971.

VI. OPTICAL DIAGNOSTICS OF HOT, DENSE PLASMAS^(*)

by

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Summary

The use of laser light as a monitor for the state of a hot dense plasma is one of the most important and reliable plasma diagnostic techniques. Problems encountered in Thompson scattering electron temperature measurements and interferometric density measurements are discussed. Finally, the possibility of two-wavelength scattering yielding a deep insight into the phase space distribution of a plasma is presented.

Introduction

It is quite clear that the experimental facts about plasmas are only as "good" as the diagnostics allow these facts to be. In other words the better the diagnostics, the better the actual physical understanding of the phenomena.

One sees this in the dynamics of fluids where the phenomena of turbulence has intrigued some of the finest minds for over a century and where there still appears to be no deep understanding of what is transpiring in nature. Of course the theoretical side of turbulence is extremely difficult because of non-linearity, but the experimental situation apparently is such that no powerful physical tools have evolved that can shed decisive insight into turbulence. (The laser combined with holography may prove to be such a tool).

We believe that a similar situation prevails in fusion research, only much worse. With this in mind, we set ourselves the task of asking, what should we measure in a plasma and how does one go about measuring it?

Clearly we have in mind plasmas of the kind encountered in Chalice, i.e. high density, hot plasmas.

The use of physical probes were ruled out immediately because of disturbance or interference with the plasma. Shooting in material beams of a well defined nature, e.g. electrons, and seeing what happens was also vetoed because the connection with what is measured and theory is too dependent, i.e., the theory is not accurate enough to interpret the dynamics of the plasma itself. Furthermore, the beam will disturb the actual state of the plasma.

The best physical candidate to study plasmas appears to be electromagnetic radiation. It interferes with the state of the plasma the least. Moreover, modern technology has provided sufficient, albeit somewhat costly, source strength. The electromagnetic radiation emitted by the

plasma (we have in mind deuterium plasma) in the form of bremsstrahlung also constitutes an excellent tool for ascertaining the state of a plasma.

Bremsstrahlung however appears to yield only very gross quantities such as temperature, whereas light scattering can be made to yield fine structure. Moreover unless one has a very pure deuterium plasma, impurities in the form of high Z and bound states can cause serious diagnostic difficulties in analyzing the emitted electromagnetic radiation.

However, the realization that electromagnetic scattering by the plasma appears to be the diagnostic tool par excellence only grew gradually. The power, scope and significance of electromagnetic scattering by the plasma still is not fully comprehended although the general (we believe correct) predictions are at hand. These are embodied in the final result for the scattered intensity, $I_{\omega}(k)$, of frequency ω and wave vector k produced by an incident field $E(x,t)$.

I. Thompson Scattering

Thompson scattering has been found to be a useful non-perturbing method for determining plasma electron temperatures.

As regards to experimental difficulties there are three regimes. For plasma density $< 10^{13}$ the cross section is so small that large input powers are required just to get a detectable signal. In the 10^{14} cc⁻¹ regime the cross section is large enough so that modest input power produces an acceptable result. As the density goes above 10^{16} the plasma light begins to compete strongly. Since the plasma bremsstrahlung depends on the square of the density and the scattering depends on the density, the ratio of scattered light to background plasma light gets smaller as n is increased further.

In the Chalice machine densities of 10^{16} - 10^{17} cc⁻¹ are encountered. Using a 1 joule 50 megawatt Q-switched ruby laser, electron temperatures have been measured with an accuracy of 50%. The low precision is due to plasma background light.

To improve the accuracy more laser power is required. This may be accomplished in several ways: A more powerful laser is the most obvious solution. This has several drawbacks, the initial cost is high and the cost for the optical components is very high, partly due to cost of higher quality lenses, etc., and partly due to replacement made inevitable by high power produced damage. Mode locking or other similar methods reduces the cost and damage problem by increasing the power but not the energy. However, the timing is not precisely controlled and thus systematic time development cannot be done. Furthermore, detectors

^(*)Supported in part by the United States Atomic Energy Commission

are not available to monitor low light levels with rise times shorter than a few nanoseconds.

We have developed a closed cavity-switchoff mode of operation which increases power and is precisely timed. It operates as follows (See Fig. (1)).

The usual pockel cell Q switch is employed. Instead of a polarizer and a 100% mirror, a birefringent prism and mirror is used. When the Q switch is off the prism directs the light out along path A. A pulse applied to the Q switch changes the polarization and the light is directed to the mirror on path B. The mirror at the opposite end is also 100% reflecting so no light leaves the cavity. The light builds up until it has reached the maximum, when the Q switch is suddenly turned off. The light stored now leaves the cavity along path A. The pulse length is simply given by the cavity length

$$\tau = \frac{2L}{c}$$

Thus for a laser cavity 30 cm long the pulse width is ≈ 2 nanoseconds. The energy is the same as for the normal Q switched pulse but the width is about 10% of the usual length. Thus the instantaneous power is increased 10 times, with a resultant increase of 10 in the signal to noise ratio in Thompson scattering.

II. Multimode Interferometry

Interferometry is one of the most important and reliable plasma diagnostic techniques available to fusion research. Two parameters that must always be considered are the plasma frequency, ω_p , and the total path-length through the plasma. The ratio of the plasma frequency to the laser frequency determines the refractive index of the plasma. If the ratio is small then the refractive index will be linear in the plasma density

$$N = [1 - (\frac{\omega_p}{\omega})^2]^{1/2} \approx 1 - 4.46 \times 10^{-22} \lambda^2 n_e, \quad (2.1)$$

with λ in microns and n_e in cm^{-3} . If we define the interferometric fringe shift, S , to be the phase shift difference of a ray traversing the plasma and a reference ray divided by π , then S is given in terms of the mean plasma density and the mean path length as

$$S = (\phi - \phi_0)/\pi = -8.92 \times 10^{-18} \lambda L n_e \quad (L \text{ in cm.}) \quad (2.2)$$

If the plasma density and path length are not adjustable then there are only two general ways to increase the sensitivity of an interferometer; to increase the wave length, or to improve upon the ability to detect a fringe shift. One of the authors has studied the latter approach and in Reference (3) a method for increasing the fringe shift resolution of a two-dimensional optical interferogram by more than an order of magnitude without loss of spatial resolution is described. A Fabry-Perot cavity is used as an interferometer in order to increase the number of passes (increase L) through the plasma. Instead of actually increasing the fringe shift the result is that the fringes

are narrowed proportionately to the number of passes. The sharpened fringes are then multiplied in number by using a multimode laser as a light source. The resulting fringe pattern is then equivalent to that of a Mach-Zehnder interferometer, except that a shift of an "effective fringe" corresponds to an optical path length difference of $\lambda/2\alpha$ (instead of λ) when the cavity lengths are in the ratio of $L/L_0 = 1/\alpha$ and α is the number of excited laser modes. Gas lasers operate efficiently with large numbers of axial modes. The He-Ne laser used in (3) had an α of 14, and effective gains in resolution of up to 40X over a Mach-Zehnder have been obtained.

The intermodel (effective) fringe shifts are given by

$$S_m = -8.92 \times 10^{-18} \alpha \lambda L n_e. \quad (2.3)$$

With laser and interferometer cavity finesses of 200 ($\alpha = 100$) and reading shifts of a 1/4 fringe ($S_m = 1/4$) from the film one would have an approximate practical limit on the measureable electron density given by

$$n_e = 3 \times 10^{14} / \lambda L \quad (2.4)$$

At $\lambda = 0.6328 \mu$, (He-Ne), and $L = 10$ cm, the corresponding density would be $5 \times 10^{13} \text{ cm}^{-3}$; and with a CO_2 laser (10.6μ) one could detect an electron density of about 3×10^{12} . Curves are plotted for arbitrary values of the various quantities at these two wave lengths in Fig. (2).

Transverse spatial resolution is determined in principle by the cavity length and the wavelength

$$\Delta x > \sqrt{L\lambda/2} \times 10^{-2} \quad (2.5)$$

And in the most sensitive case mentioned, the spatial resolution would be limited to about 1mm.

The Application to the Chalice Experiment

A less sensitive experiment using equal cavity lengths and 50% R mirrors has been completed. In the Chalice experiment the θ -pinch coils are 1.5" in diameter and 2 3/4" long with 1-1/8" outer mirrors. They are separated by 3/4" and driven in anti-parallel. Peak fields in the θ -pinch region are 60kg and 44kg at the cusp line-escape. The rise time of the fields is 1 μsec and the crowbar time (half life) is 25-30 μsec . With initial D_2 filling of 120 and 2-pinch preheating the plasma which initially appeared in the cusped region of the magnetic field at approximately peak field of the θ -pinch was observed to have toroidal symmetry. The plasma had a well defined boundary (an inverted parabola) in the Z-direction with a width of 6mm. The radial distribution, after Abel inverting, was found to peak just inside of the line escape at $n_e = 5 \times 10^{16} \text{ cm}^{-3}$. The density on the center line being about 3×10^{16} . The fringe shift in this case is just equal to one fringe with a power of 2X, i.e. $\alpha = 1$. Since the plasma was viewed through 4 surfaces of uncoated windows which had a net flatness of 1/2 - 1 fringe densities below

those mentioned above are not readily discernible. This meant that at times prior to or later than those for which the plasma was dynamically compressed, little quantitative information could be obtained. Ruby laser energies of 10 mJ were employed to obtain the photographs using a camera with no lens or shutter. A #89B Wratten filter and Polaroid films #55p/n and 57 were used in combination as an effective filter; passing the laser pulse at sufficient levels to photograph but restricting both room light and a D.C. 1 mW HeNe alignment laser to insignificant power levels (i.e. > 1 day exposure).

A vacuum tube with diametrically opposite flanges for mounting a pair of optical viewing ports has been ground and polished by hand to accept a pair of 1/20 wave flats (Coated for 95% reflectance at both 6328 and 6943 Å). The etalon orientations are temporarily adjustable by rocking slightly on the 10 fringe flat flange with spring tension. The final orientation will be fixed by epoxying the windows in place with the tube coupled to the vacuum system, permitting observation and correction of the fringe orientation during cure. The mirror separation is 10 cm. A Q-switched ruby laser with an adjustable cavity length will be used as the primary light source.

The temperature-tuned mode selector of the laser is known to produce 1, 2 or 3 modes in excess of 1 meter coherence length each. More modes may be manufactured by replacing the mode selector with a simple dielectric front mirror and varying the capacitor voltage. It is not critical that the laser always produce the same number of modes (or even the same modes). It is sufficient that the number of modes be approximately equal to or larger than the cavity length ratio L_0/L_p . In our case about 6, it is anticipated that a plasma density in excess of 10^{16} cm^{-3} with a diameter of 3 cm should be clearly delineated. The mirror separation may be doubled if necessary to investigate even more detailed plasma structure.

Other Applications

In any interferometric application where lengths are monitored by counting fringes one may, by utilizing the multimode technique, introduce finer fringe structure much like the subdivision scales of a ruler, e.g. every tenth fringe could be made more intense than the others.

III. Analysis of Plasmas With Two Wavelengths of Incident Radiation⁽¹⁾

3.1 Introduction

Thompson scattering only reveals the velocity distribution along the direction $k-k_0$, where the direction k of the scattered radiation is fixed (in Chalice it is 90° with respect to k_0 where k_0 is the wave vector of the incident radiation).

It cannot tell us anything about the full velocity distribution $f(v)$ unless measurements are taken for all directions $k-k_0$, a hopeless task

experimentally.

More importantly nothing can be revealed concerning the full phase space distribution $f(x,v,t)$ except for an average density of particles in a scattering volume delineated by the laser beam and the optics of the monochromator.

To obtain the full $f(x,v)$ would be extremely important in understanding plasma microinstabilities, plasma turbulence, etc.

3.2 Intensity of Scattered Radiation

Percus and Yevick⁽¹⁾ have shown that the intensity of scattered radiation in the direction of $\hat{k}$ and having frequency ω is given by

$$I_\omega(\hat{k}) = \frac{\nu_0^2}{2} \left(\frac{e^2}{2m} \right)^2 \int \dots \int \hat{k} \times E(\hat{k}_1, \omega_1) \cdot \hat{k} \times E^*(\hat{k}_2, \omega_2) \cdot f_{k_1-k_2}(v) \delta(\omega - k \cdot v - \Omega) \delta(\omega_1 - k_1 \cdot v - \Omega) \delta(\omega_2 - k_2 \cdot v - \Omega) \frac{d\omega_1}{\omega_1} \frac{d\omega_2}{\omega_2} d\Omega dk_1 dk_2 dv \quad (3.1)$$

$E(k_1, \omega_1)$ is the Fourier amplitude of the incident radiation and $f_k(v)$ is the spatial Fourier transform of phase space distribution $f(x,v)$

$$f_k(v) = \frac{1}{(2\pi)^3} \int e^{ik \cdot x} f(x, v) d^3x \quad (3.2)$$

The above has a basic assumption that the frequency is sufficiently high so that the plasma dielectric constant may be taken as unity and a high enough wave vector such that the incident beams see effectively free electrons.

From Eq. (3.1), it is clear that the incoming waves (k', ω') and (k'', ω'') will be mixed by the particle at velocity v if they have the same Doppler shifted frequency Ω in the frame of the particle. They will then detect a spatial variation at wave vector $k' - k''$ and radiate at a (k, ω) with the same Doppler shifted Ω .

3.3 Special Case of Thompson Scattering

Thompson scattering is a special case of Eq. (3.2) wherein the incident wave is given by

$$E(k, \omega) = E \delta(k - k_0) \frac{1}{\pi} \sin \frac{T}{2} (\omega - \omega_0) / (\omega - \omega_0), T \rightarrow \infty \quad (3.3)$$

In that case the intensity of scattered radiation in direction k and having frequency ω is given by

$$I_{\omega}(\hat{k}) = \frac{\mu_0}{2} \left(\frac{e^2 \omega}{2m \omega_0} \right)^2 |\hat{k} \times \mathbf{E}|^2 / (|\hat{k} - \hat{k}_0|) \quad (3.4)$$

$$\cdot \int f_0 \left(\frac{\omega - \omega_0}{|\hat{k} - \hat{k}_0|}, v \right) dv$$

Therefore the velocity distribution perpendicular to $\hat{k} - \hat{k}_0$ is integrated out. In short, we measure only the velocity distribution along $\hat{k} - \hat{k}_0$. We observe moreover that only the average spatial density is obtained, not $f_{\hat{k}_1 - \hat{k}_2}(v_n)$. Clearly, $f(x, y, t)$ can only be obtained by using more than one incident $\hat{k}$ as we can observe from Eq. (3.1).

3.3 Two Wavelengths Incident on the Plasma

Suppose we consider a laser that has multiple λ outputs. With suitable filters and mode selection let only two different λ 's exist, i.e. λ_1 and λ_2 .

Assume that the directions of $\hat{k}_1$ and $\hat{k}_2$ are known, then according to Eq. (1)

$$\omega - \omega_1 = (\hat{k} - \hat{k}_1) \cdot \mathbf{v} \equiv |\hat{k} - \hat{k}_1| v_1 \quad (3.5)$$

$$\omega - \omega_2 = (\hat{k} - \hat{k}_2) \cdot \mathbf{v} \equiv |\hat{k} - \hat{k}_2| v_2 \quad (3.6)$$

with v_1 and v_2 defined as above

Hence for a fixed $\hat{k}_1$, $\hat{k}_2$, and $\hat{k}$ (which of course determine ω_1 , ω_2 , and ω), Eqs. (3) and (4) fix the velocity components v_1 and v_2 in the directions of $\hat{k} - \hat{k}_1$ and $\hat{k} - \hat{k}_2$. Hence the velocity in the plane determined by the two directions $\hat{k} - \hat{k}_1$ and $\hat{k} - \hat{k}_2$ is fixed. There still remains the velocity component v_3 in the direction perpendicular to the plane of $\hat{k} - \hat{k}_1$ and $\hat{k} - \hat{k}_2$ which remains undetermined

$$\mathbf{v} \cdot (\hat{k} - \hat{k}_1) \times (\hat{k} - \hat{k}_2) = \mathbf{v} \cdot (\hat{k}_1 \times \hat{k}_2 + \hat{k} \times (\hat{k}_1 - \hat{k}_2)) \quad (3.7)$$

$$\equiv v_3 |(\hat{k}_1 \times \hat{k}_2 + \hat{k} \times (\hat{k}_1 - \hat{k}_2))|$$

Therefore the intensity given by Eq. (1) for the scattered radiation in the direction of $\hat{k}$ caused by two incident beams $\hat{k}_1$ and $\hat{k}_2$ is given by

$$I_{\omega}(\hat{k}) = \frac{\mu_0}{2} \left(\frac{e^2 \omega}{2m} \right)^2 \frac{1}{\omega_1 \omega_2} (\hat{k} \times \mathbf{E}(k_1, \omega_1)) \cdot (\hat{k} \times \mathbf{E}(k_2, \omega_2)) \cdot \int f_{\hat{k}_1 - \hat{k}_2}(v_1, v_2, v_3) dv_3 \quad (3.8)$$

3.4 Application of the Theory

A dye laser is capable of generating a whole host of frequencies. Moreover, the dye laser has the potential of tremendous power output, an absolutely essential requirement in 2-v scattering. Therefore an entire "bag of tricks" becomes technically feasible. Coupled with the above theory, the full mapping of $f(x, y)$ is possible and highly desirable.

The physical nature of plasma micro-instabilities, vortices, eddies, etc. is in the realm of

the possible. We have in mind the ability to go down to a fine microscopic level perhaps as much as half the wavelength of light.

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Fig. (1) Block Diagram of Closed Cavity Switchoff Laser System. Beam A resonates within the cavity when the pockels cell is activated, when it is switched off the polarization is rotated and it exits at B.

Fig. (2) Electron density versus pathlength-mode number per nodal fringe shift product, for He-Ne and CO₂ wavelength.

VII. Development of Project Chalice

By far the greatest bulk of time and effort in the Chalice Project went into the solution of difficult engineering problems. These problems, which superficially appear simple, can be incredibly complex, time consuming, and exasperating, and yet the success or failure of the project depended upon their solution. In many ways it was a bitter experience, guaranteed to make a person humble.

In the first year of the Chalice Project, the capacitor system had already been constructed for another experiment. We seriously believed that the Chalice experiment would be over within at most 18 months, i.e. whether or not high density, long confinement time prevails for hot plasma while using two θ -pinches and a cusp. Our faith rested in the belief that the hard work of constructing a fast bank was behind; all that remained was hooking a pair of coils into the system and then seeing what there is to see. Little did we realize the long agony of years of hard work that would have to lie ahead.

After six months of building coils and massive copper collector plates, we began to fire the system. Initially we worked at 10 kv or so, and began to collect streak and frame pictures of the plasma without warning, our problems began to multiply. In going to 15 kv, the switches would start to break-down. Years of experience later we can see why the switches would have had to break-down.

The initial switches were plasma switches, i.e. several button guns in parallel which, upon triggering, closed the gap. For a plasma

switch to work, the pressure must be low (around a micron). However, after several firings, conducting paths would form between the high and low potential. Moreover, the inductance was intrinsically high, a problem that could be solved only by having a number in parallel but a number in parallel brings additional problems, i.e. enhanced probability of malfunctioning.

Besides the switching problem, the transmission lines were breaking down. The reason for this was that the quality of the epoxy deteriorated with age.

Because of failure to go to higher voltage, and because 64 valuable high voltage, fast capacitors were available, we embarked on the construction of a fast θ -pinch bank. Little did we realize the technical problems this entailed, and three years went rapidly by before the end was in sight.

Aside from the obvious one of abundant capable manpower, the secrets to engineering are ingenuity, persistence, and most important of all, rigorous testing of components under conditions as closely identical to real operating conditions as possible. It is the latter that is hard to come by, especially if pressed for time. On some components, such as switches and transmission lines, we satisfied this criterion; on other problems such as mechanical shock of the coils, better dielectrics, etc., time and manpower were simply not available. On a difficult problem, it is working against a time limit plus adequate man power (the two are related) that constitute the greatest bottlenecks to rapid advance. Yielding to temptation to cut corners means paying a price at a later date.

The major engineering achievements of Chalice were the following:

(1) Very fast, dielectric, high voltage, high current switches.

These switches utilize exploding wires and can be fired in parallel to within a tenth of a microsecond. The inductance of the switches is very low. There is one major defect with dielectric switches, i.e. they are good for one shot only, and the time required for changing switches can be annoying.

(2) High Voltage (50 kv) low inductance transmission lines.

Here the major problem is corona and this was solved by making the center hot conductor of a three conductor transmission line (ground, hot, ground) rounded and not aligned with the two grounds.

(3) High voltage, corona free connectors. Here the problem

is how to connect transmission lines to a collector plate. This is not so simple as it sounds because of high frequency corona. The solution lies in rounding the grounds of the transmission line and collector plate into tabs and using a rounded box, shaped similarly to a cover of a bar butter plate, to join the two.

(4) Novel coil design, allowing greater flexibility of coil construction. The coil shapes in Chalice are somewhat

complex. The basic idea is to have our inner lining made of copper surrounded by a strong steel jacket. The feed-ins into the coils are a real problem because of space boundary conditions. By making the feed-ins from flexible copper sheets we were able to solve the space problem. Interestingly enough, this arrangement was tested out and found to withstand very high currents.

- (5) Fast high voltage light triggers. Here the problem is to isolate electrically a screened data room from the noises generated by the various banks firing. The different delay signals are transmitted across the screen room via optical fiber light pipes. The light is generated by a very fast flash tube and picked up on the outside by a photodiode. To generate a fast pulse with a rise time of 50 nanoseconds and a height of several hundred volts is not simple⁽⁸⁾.
- (6) An inexpensive, reliable Mach-Zehnder Interferometer (See Chalice Annual Reports for 1965-66 and -67). The problems we faced here were both lack of money and very tight spatial problems. The Mach Zehnder took 3 months or so to build; but once having built it, the problem of finding white light fringes confronted us. For six months we searched and searched and could not find them. The final solution came with 75 cents worth of rubber bands! The reason for this difficulty lay in the fact that our system was rigidly mounted and located on the sixth floor.

The shaking of the building, the vibrations of the floor and ceiling, caused the Mach Zehnder to zoom back and forth thru the fringes. Instead, by suspending the system with rubber bands, we mechanically isolate the system. Friction between parallel rubber bands dampens out the vibrations.

The elegance of this method lies in the fact that an interferometer need not be heavy (ours weighed only around a hundred pounds), that it can satisfy the most awkward spatial boundary conditions, and last but not least, that it is quite inexpensive.

VIII. Theoretical Work

We are a firm believer in a synthesis of experimental and theoretical work. There are many reasons for our belief, but this is not the place to list them. We tithed a portion of our time to theoretical problems. Some of them were as follows:

- (1) The nature of the snow plow shock in Chalice. Here, because of geometry, it is not easy to find the nature of the shock surfaces. The same problem arises in the plasma focus experiments. Again, the simplest model is constructed, hoping to find some correspondence with nature. The major assumption of an infinitely thin sheath is not borne out by our experimental data.

- (2) Inhomogeneous collective coordinate. The line of approach that we have followed for many years has been that of collective coordinates, or normal modes. Only recently has some interest grown among the body of plasma physicists along this direction.

In homogeneous collective coordinates are those normal modes appropriate for a particular non-uniform density. E.g., in Chalice, these turn out to be Bessel functions, and not exponentials.

- (3) Calculation of magnetic fields. The calculation of plasma free pulsed magnetic fields of the type employed in Chalice experiment is not easy; indeed it is extremely difficult because of the nature of the boundary conditions. A new variational approach to the problem has been worked-out. Unfortunately, we have not had time to push this line of attack more deeply.

- (4) Two body correlation functions. (See also Chalice Annual Report for 1963-64). The equilibrium two-body correlation lies at the essence of statistical mechanics. We have worked out a theory which incorporates into the approximation both the long range nature of the force of interaction between particles as well as the short range (hard core). The resulting theory we believe will be of considerable aid to plasma physicists once the two body correlation function can be easily measured by experimentalists.

- (5) Supercollective coordinates. (See also Chalice Annual Report for 1964-65). The dynamics of plasmas is exceedingly rich and the essential problem of the decay of orderly motion into chaos still eludes our grasp. Basically, this work is in this direction. The fundamental idea here is that the stiffness constants and mass of the normal modes of a plasma are time dependent and depend in a profound way on the motion of the system as a whole.
- (6) Direct correlation function in space and time. (See also Chalice Annual Report for 1966-67). We have found an approximate expression for the space-time direct correlation function which we believe and hope will be of great use to plasma physicists. The importance of the space-time direct correlation function cannot be overstressed since it contains within it the key to a great body of physics. If we know the two body-time dependent correlation function well, it is no exaggeration to say that we will have made a big step in knowing plasmas well.
- (7) Micro-Structure Analysis of Plasma Dynamics by Means of Doppler Shifted Schlieren Holography (DSSH). The central aim the experimental study of plasma dynamics is an accurate measurement of the one body distribution function, $f(x, y, t)$. One method consists of measuring the scattered radiation

emitted when two different beams of radiation are incident on the plasma. The information obtained thereby is much richer than Thompson scattering. We now propose a second method for measuring $f(x, y, t)$. This method involves the use of holography, but with a basic difference: the reference beam is shifted in frequency from the scene beam. The theory of doppler shifted holography was worked out. The frequency shifts are generated by gradients in the density and the local velocity of the medium. Hence, a natural way to measure the local velocity is by means of doppler shifted schlieren holography (DSSH). Various experimental set-ups to accomplish this, including the problem of frequency shifting (biasing) the reference beam were analyzed.

- (8) Sampling Methods for Many-Body Dynamics. Analysis of many-body dynamics is facilitated by concentrating attention upon approximate normal modes, variables which would behave in a simple regular fashion for some approximation to the system at hand. These are coupled in the course of the actual motion. The qualitative nature of the coupling can usually be specified by division of the modes into a small number of categories, eg phonons, rotons, thermions. The structure of each category can be described by relatively few parameters, which we choose as a sample of modes. One

can then follow the time course of the system numerically, varying the sample at each time step for maximum efficiency and using one of many possible moment algorithms for redescribing in terms of the new chosen sample.

- (9) Dual-Time Expansion Method for Classical Many Body Dynamics. The normal mode concept for interacting classical particle systems has a wide range of validity in frequency and wave vector space. We proposed a particularly simple perturbation expansion for correcting the zero order dispersion relation which this concept entails. The key to simplification lies in the introduction of the microscopic velocity field, in terms of which the equations of motion have a simple bilinear form. The microscopic velocity field is still not deeply understood, in particular the multi-valued nature that appears to exist in the inter-particle vacuum space. Nevertheless, because of the simplicity of the basic equations, the velocity field appears to have great physical significance for the many-body problem. In this study, we were particularly interested in the long time development of an initial fluctuation in an otherwise equilibrated particle system. The technique of singular perturbation theory for stochastic differential equations demands the introduction of at least two time scales. The first order perturbation

matrix in the present formulation commutes with the zero order matrix, retaining the nature of the normal modes, but altering the dispersion relation and introducing attenuation. The results of this analysis will be presented for several different interaction forces.

IX. Recommendations

As a result of our years of experience, perhaps it may not be out of order to suggest a few proposals.

One of the most severe limitations in the controlled fusion work relating to high density experiments such as Project Chalice is the need for very high magnetic fields approaching the megagauss value. In order to attain such fields a whole new technology is required wherein reliability, low cost, and ease of handling prevails.

We believe it would be advantageous to have a highly competent group of scientists and engineers comprising a Plasma Components Center in the Controlled Thermonuclear Fusion Program who do nothing but worry about the "nuts and bolts" for the plasmas effort-such as dielectrics, capacitors, switches, etc. (See list of problems in Sect. (VII)). They should be daring enough to think and test out in radical ways, e.g., to store large quantities of energy (other than in a capacitor) capable of being called upon in extremely short times.

As an example of the difficulties involved in the Chalice Experiment the problem of extremely good dielectric materials able to handle

very high volts stressing cropped-up repeatedly.

Another example is an inexpensive very low inductance, high voltage, high current switch. Despite an enormous amount of work, we feel that only the surface has been scratched in this direction. The use of high powered lasers to close the switch seems like a promising line of development.

Still another example of the kind of problems encountered in Project Chalice is a need for an inorganic high mechanical shock resistant material to replace pyrex glass or ceramic for the plasma chamber.

The above problems may appear to be prosaic, but like the nuts and bolts in a car, we believe that they are essential and of great importance to the success of high density pulsed plasma work, and indeed once one grapples seriously with any one of them, what appears to be prosaic becomes exciting and challenging.

The Plasma Components Center is to be strategically located in the country where one has a capability of closely working with industry in the development of needed components.

Furthermore, the Plasma Components Center should provide experts "on tap", for any given hardware problem that may arise throughout the country. E.g., a particular capacitor for a particular need, where available, how much does it cost, etc. This can save, in the long run, a great deal of time and money.

The second recommendation is a Plasma Diagnostics Center for the AEC-ETP effort. What we have in mind here is a bank of experts, one specializing in optics, another in high energy radiation detection, etc. These scientists also should be on tap to advise and at the same time act as a clearinghouse of information. Some diagnostic techniques, e.g., the Mach Zehnder, Thomson Scattering, etc., are subtle and the "confidence time" enormously shortened by several days of training with an expert. But even more important, an expert in optics, e.g., tends to innovate new diagnostic tools and these are badly needed in plasma work. As an example, one would like very much to measure the one body distribution function $f(x, v)$ as a function of time for both electrons and ions. What is the best way for doing this?

X. Some Basic General Remarks

We were among the first to have foreseen the present Energy Crisis. This was the fundamental motivation for Project Galileo.

What we little understood and now fully comprehend is the magnitude in dollars required to do the job. During the entire period of research we were always plagued by lack of well trained supporting staff, in particular, engineers and technicians.

At no time were there more than five full-time people on the project because that is all the budget could provide. In reality ten times that

number could easily have been fully utilized in a constructive manner.

The concept that like in war, enormous waste must not only be tolerated but expected was and undoubtedly still is totally alien to the fusion program. For indeed a war is going on, the search by mankind to rid itself from fossil fuel. Waste is an essential ingredient in the military in order to provide for many diverse contingencies. The same must be true in CTR.

One really does not know what are the "missing links". Poor capacitors, high inductance, low voltage operation, poor diagnostics, poor theory, which ones are keys to success?

One thing is certain, above all, in magnetic confinement work. There appears to be a technological wall in the magnitude of the magnetic field against which the scientist repeatedly is confronted. How to break down that wall is of the utmost importance in the magnetic confinement approach to CTR.

The perfection of a switch or capacitor is extremely expensive and little likelihood of immediate "fall-out" or profit for industry. Only society as a whole, working through its government, can finance such extraordinary costs that must be met.

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