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Abstract

Thomson scattering has been used to measure the time resolved spectrum of ion wave decay products from two instabilities which can limit the growth of Stimulated Raman Scattering (SRS). This experiment detected ion wave decay products far above the thermal level and demonstrates that SRS produced Langmuir waves' undergo the Langmuir Decay Instability (LDI) in ignition relevant plasmas. Product waves of the Electromagnetic Decay Instability (EDI) were not detected.

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Langmuir wave growth and saturation in plasmas is of great importance to inertial confinement fusion (ICF) applications, where Langmuir waves can reflect large fractions of the incident laser energy via the process of Stimulated Raman Scattering, or SRS [1]. In SRS, the incident laser wave resonantly drives a Langmuir wave and a scattered electromagnetic wave [2]. Understanding the mechanisms which govern the reflectivity under the conditions of ignition experiments is critical to allow scaling to fusion reactors [1].

Recent studies have suggested the importance of Langmuir wave decays to SRS. Numerous theoretical treatments have shown that strongly driven SRS can be affected by Langmuir wave decays and collapse [10–13]. Recent experimental studies of SRS in large scale plasmas have found reflectivities that scale weakly with plasma properties [3–6] consistent with SRS being saturated. These experiments have shown that SRS can be limited by non-linear saturation of the SRS Langmuir wave [14], and that the saturation amplitude is dependent on the ion acoustic wave damping rate in the plasma [4,5] suggesting that an ion wave decay is the cause. Two processes in which the Langmuir wave decays into an ion wave and a third wave are likely candidates to explain this behavior. In the Langmuir Decay Instability (LDI), the third wave is a Langmuir wave. This process has been suggested as the likely SRS saturation mechanism by many analytic and numerical studies [10–13]. Recent experiments in small scale plasmas have also detected decay products attributed to the LDI instability [7–9]. Another possible mechanism is the Electromagnetic Decay Instability (EDI), where the third wave is an electromagnetic wave. This instability has a lower threshold than LDI, and also a weaker growth rate [15]. In each case, the gain of the instability is peaked when the ion daughter wave nearly co-propagates with the SRS Langmuir wave.

In this Letter, we present the first demonstration that SRS-produced Langmuir waves decay by the LDI process in ignition-relevant plasmas, as predicted theoretically [10-13,15] and consistent with recent experiment [4,5,14]. We have performed experiments in which the Thomson scattering geometry is designed to be sensitive to the ion wave products of either the LDI or the EDI process, and observed ion waves only for the LDI case. Ion waves produced by these decay processes have the important characteristic that the waves' $\bar{k}$ and ω

are unique, so the $\bar{k}$ resolved Thomson measurements can identify the individual instability. Ion waves are also a clearer indication of the LDI instability than the counter-propagating Langmuir wave observed in colder plasmas [7,8] as they cannot be due to back reflection of the primary wave or driven by other sources [8].

Nova

The experiments were performed at the NOVA laser facility [1]. The experimental configuration is shown in figure 1. The plasma is produced by a gas filled balloon target which is heated by 8 unsmoothed Nova beams with a wavelength of 351 nm to produce a 2 mm diameter uniform density plateau with an electron temperature near 2.5 keV and a density determined by the gas used [16].

Thomson scattering [18] is used to detect the ion wave decay products of SRS Langmuir waves driven by a separate drive beam. The Thomson scattering probe beam is a low energy (50 J) F/16 beam of 263.5 nm wavelength. The Thomson scatter signal is focused by an F/10 cassegrain optic onto the slit of a 1-meter spectrometer coupled to a streak camera to provide time and wavelength resolution of the waves, as well as spatial localization within a volume of approximately (200 μm)^3 set by the spectrometer slit. The coherent Thomson scattering $\bar{k}$ matching relations determine the direction of the scattered light from a given wave, and also determine the angle at which the probe must intersect the wave. In the present experiments, the frequency of the SRS scattered light from previous experiments was used to determine the $\bar{k}$ of the SRS langmuir wave. Models of the decay processes [11,15] were used to predict the LDI and EDI wave$\bar{k}$'s, and hence to choose the drive beam location and to position the collection optic. The streaked spectrum was used to identify ion wave signals by the characteristic narrow lines shifted by $\nu_{ion-acoustic} \approx 0.4$ nm from the probe beam wavelength.

The SRS drive beam's wavelength and angle to the probe beam were chosen to satisfy the Thomson scatter $\bar{k}$ matching criteria for either LDI or EDI. For the LDI experiment, the SRS drive beam wavelength is 526 nm. The spot size of the drive beam at the location probed by the Thomson scattering diagnostic was either a defocussed 600 μm spot (I_0 = avg. intensity $= 6 \times 10^{14}$ W/cm^2), or a RPP-smoothed best focus spot of 320 μm ($I_0 = 2 \times 10^{15}$ W/cm^2).

For the EDI experiment, the drive beamspot was defocused to 320 μm ($I_0 = 2 \times 10^{15}$ W/cm^2). The 6×10^{14} W/cm^2 intensity has a comparable electron v_{osc}^2, and therefor SRS gain, to an intensity of 2×10^{15} W/cm^2 at 351 nm, allowing comparison of LDI and EDI under similar gain conditions.

In order to keep the relative densities the same ($n_e = 0.10 n_c$) for the LDI and EDI experiments, the gas mixture is changed. For the LDI experiments ($\lambda_0 = 526$ nm) the gas is C_2H_6, while for the EDI experiments ($\lambda_0 = 526$ nm), the gas is C_5H_12. LASNEX predictions of target conditions for both targets show $T_e \approx 2.2$ KeV, and $T_i \approx 0.3 - 0.4$ KeV [17]. X-ray spectroscopic studies and thermal Thompson scattering measurements of similar targets have confirmed the calculated values of plasma density and temperature [16]. The plasma conditions have been chosen to be relevant to ignition experiment conditions, where it is expected that the laser will encounter a few- KeV plasma of about $10\% n_c$, at an intensity of about 2×10^{15} W/cm^2 at 351 nm [1,3].

To establish the existence and properties of the primary SRS Langmuir wave, a separate diagnostic beam with an SRS backscatter measurement station was run with the same timing, focus, and intensity as the drive beam. This beam was pointed at the same target radius to encounter similar plasma conditions in the spherically symmetric plasma as the drive beam but not intersect it. This allowed measurement of SRS scattering under the same conditions as the decay measurements.

The SRS measurement from the diagnostic beam during the LDI measurement is shown in Figure 2. The beam timing is such that all beams are 1 ns in duration, with the SRS drive beam, SRS diagnositic beam, and the Thomson Scatter beam turning on 0.5 ns after the heaters as shown in the figure. The narrow feature at 815 nm is SRS from the plateau density of $9 - 10\% n_c$. The existence and position of the narrow feature confirms the simulated plasma density. The power scattered in the 815 nm feature was found to be $\approx 0.6\%$ (time averaged) of the incident power, and this reflectivity varied less than 25% as the drive beam's intensity was varied by a factor of two. Such a weak dependence on intensity is not consistent with a linear three wave process, and is consistent with models of Langmuir wave saturation

[10–13]. The broad feature from 700 – 800 nm may be due to SRS occurring in the low density halo plasma formed by blow off around the gas bag. The features at 527 nm are a combination of stray light from the heater beams and stimulated Brillouin scattering from the target, which comprises approximately 1 – 2% of the incident energy and provides a wavelength fiducial. This feature is entirely turned off at the time when LDI activity occurs, indicating that very little or no SBS is occuring in the plasma at this time.

The LDI ion wave Thomson scattering spectra is shown in figure 3a. The Thomson scatter spectrometer imaged the region $r = 700 \pm 100$ μ m from the gas bag center on the side closer to the drive beam entrance and the collection optic was set to measure the LDI ion wave $\bar{k}$. Drive beam intensity was 6×10^{14} W/cm^2. Clearly visible is the narrow band structure consisting of two bright lines near 263.5 nm, with one of the lines very close to unshifted. The spacing between the lines is $\approx 0.4nm$, which is consistent with scattering from an ion wave with the predicted LDI wavenumber propagating in these plasma conditions. The absolute frequency of the lines may be shifted by flow velocities in the plasma. Simulations show that during the late time interval when SRS is observed (t = 1.2 to 1.5 ns), rapidly varying sonic flows exist in the vicinity of $r = 700\mu$m with gradient scale lengths of 100 - 300 μm which will shift the ion wave frequencies in the scattering volume sufficiently that the absolute frequency shift of the waves is difficult to predict. However, the observation of narrow lines that are within 1 nm of the wavelength of the incident Thomson beam is consistent with scattering from ion waves in these plasma conditions which have the $\bar{k}$ predicted for LDI.

Other features of the Thomson scattering spectrum are also consistent with LDI activity. The ion wave scattering occurs at the time where SRS backscatter is observed to be largest. On a shot where the SRS drive beam was removed all signal disappeared except for the least shifted narrow band signal which appeared at a much reduced amplitude (figure 3b). This is consistent with these lines being due to waves driven by the pumping beam. Two sharp temporal bursts are apparent in the ion wave feature, while the SRS reflectvity is relatively constant. This may be due to the fact that the SRS measurement is integrated over the whole path of the drive beam, while the Thomson scatter probe samples only a small portion ($\approx (200\ \mu\text{m})^3$ out of a 600 μm diameter, 2000 μm long beam). Models indicate that SRS can fluctuate in small regions of the beam while the spatially integrated reflectivity fluctuates much less [11], consistent with both the Thomson and the SRS measurements. The peak signal from the waves driven by the pump beam is at least a factor of 10^3 in intensity above the thermal scattering level in these plasmas, indicating that the waves are being strongly driven. Subsequent shots at the same beam pointing showed results similar to those shown. This data shows that LDI is occuring at rates that drive the ion wave far above thermal levels when SRS reflectivity is large and does not vary with drive beam intensity, which is the primary result of this letter. In addition the LDI ion waves occur in conditions where previous experiments have showed the SRS Langmuir wave was non-linearly saturated [14] and are consistent with LDI saturating SRS.

The measurement of LDI ion waves was repeated at a radius of $400 \pm 100\ \mu$m with an increased intensity 2×10^{15} W/cm^2 produced with the reduced spot size of a focused, phase plate smoothed beam, and no activity was observed. This implies that LDI is most active in the outer region of the gas bag, which is consistent with previous measurements which suggest that SRS occurs primarily in the outer region [19] and with the model of strongly damped Langmuir waves which shows that scattered waves grow in the direction toward the incident beam.

These experiments were repeated for the EDI ion wave. Pointing was varied from $r = 700 \pm 100\ \mu$m from the gas bag center on the side closer to the beam entrance to $r = 400 \pm 100\ \mu$m from the gas bag center on the side away from the beam entrance. The intensity of the drive beam was 2×10^{15} W/cm^2. No ion waves above thermal level were detected in any of the EDI cases studied. The sensitivity of the detector was roughly the same as that in the LDI case for measurements at the location where LDI was detected, and should have detected a signal $\approx \frac{1}{1000}$th of the LDI signal. At other locations, due to different filtration and stray light , the sensitivity was sufficient to have detected a signal $\approx \frac{1}{10}$ of the observed LDI signal. The absence of EDI waves suggests that EDI is not playing a role in saturating SRS in these experiments.

The data has been used together with analytical formulae to make simple limiting estimates of the possible effect of the LDI process on SRS in these experiments. The amplitude of the driven ion wave was estimated using the collective Thomson scatter equation which relates scattering from a wave to rms wave amplitude:

$$(\frac{\delta n}{n})^2 \approx 16\frac{P_{scattered}}{P_{inc.}}(\frac{n_c}{n})^2\frac{1}{k^2 L_s L_c F} \tag{0.1}$$

following Ref. [20], where $P_{scat,inc}$ are the scattered and incident powers respectively, n, n_c are the electron density and the critical density, k is the wave number of the incident beam, L_s is the length of the scattering volume, L_c is the smaller of the coherence length of the wave or speckle size (4μm), $\frac{\delta n}{n}$ is the electron density perturbation amplitude of the ion acoustic wave, and F is the volume fraction that is SRS active. We can make estimate an upper limit to F by requiring that the SRS gain calcuated for our conditions is sufficient for the instability to grow from noise in the activie regions. The SRS gain in the present case is $G^0_{SRS} \approx 2.5\frac{I}{I_0}$ (weak damping limit) where I_0 is the average intensity in the laser spot, so that for SRS to be active $\frac{I}{I_0} \geq 4$ is needed and hence for a speckle intensity distribution the maximum volume fraction is $F = 0.02$ [21]. We then obtain $(\frac{\delta n}{n})^2 \geq 1 \times 10^{-5}$ as the lower bound on the electron density fluctuation associated with the LDI ion wave in these experiments. This result depends inversely on the coherence length of the wave which is assumed no shorter than a speckle size.

The inferred LDI wave amplitude may be compatible with the ion wave amplitude necessary to significantly limit the amplitude of the SRS generated Langmuir wave. Solution of the coupled mode equations in 1-D (which is appropriate for backscatter) yields the ion wave amplitude needed to effectively double the damping rate of the incident Langmuir wave, and thereby make make the wave response significantly non-linear [22]:

$$(\frac{\delta n_i}{n_{0i}})^2 = \frac{4\nu_L}{\omega_p} \tag{0.2}$$

where $\frac{\delta n_i}{n_{0i}}$ is the density perturbation amplitude of the ion acoustic wave, and ν_L is the Langmuir wave damping rate. The Langmuir wave can hence be more easily saturated in strongly driven plasmas where damping is weaker. Damping for a maxwellian electron distribution is dominated by Landau damping. There are however many mechanisms which may distort the electron distribution and lead to reduced damping in these plasmas, including trapping of particles when the waves have large amplitudes [14], non-local heat transport, and super-gaussian distributions produced by intense inverse bremsstrahlung heating by the laser. The latter effect has recently been shown to produce dramatic reductions in the damping rate of the Langmuir wave [23]. This effect can potentially reduce the damping to the collisional value as a lower limit. The ion wave amplitude to saturate SRS is then between $(\frac{\delta n_i}{n_{0i}})^2 = 0.02$ using the Landau damping rate of the Langmuir wave in a Maxwellian plasma, and $(\frac{\delta n_i}{n_{0i}})^2 = 2 \times 10^{-6}$ using the electron collisional damping rate. Hence if damping rates are reduced significantly from Maxwellian Landau levels, the observed Thomson signals are compatible with ion waves large enough to saturate SRS.

In summary, Thomson scattering measurements in a large scale plasma have detected ion waves far above the thermal level which are identified by their wave vector, spectral structure, and correlation with SRS activity as decay products of the Langmuir Decay Instability driven by SRS produced Langmuir waves. The ion wave amplitudes are consistent with saturation of SRS under damping conditions in a non-Maxwellian plasma such as those seen in many theoretical studies [12,13,23]. The Electromagnetic Decay Instability was not observed in similar experiments. These measurements are the first demonstration that SRS produced Langmuir waves undergo Langmuir decay under the conditions expected in ignition experiments as was suggested with by previous studies of SRS saturation [4–6,14].

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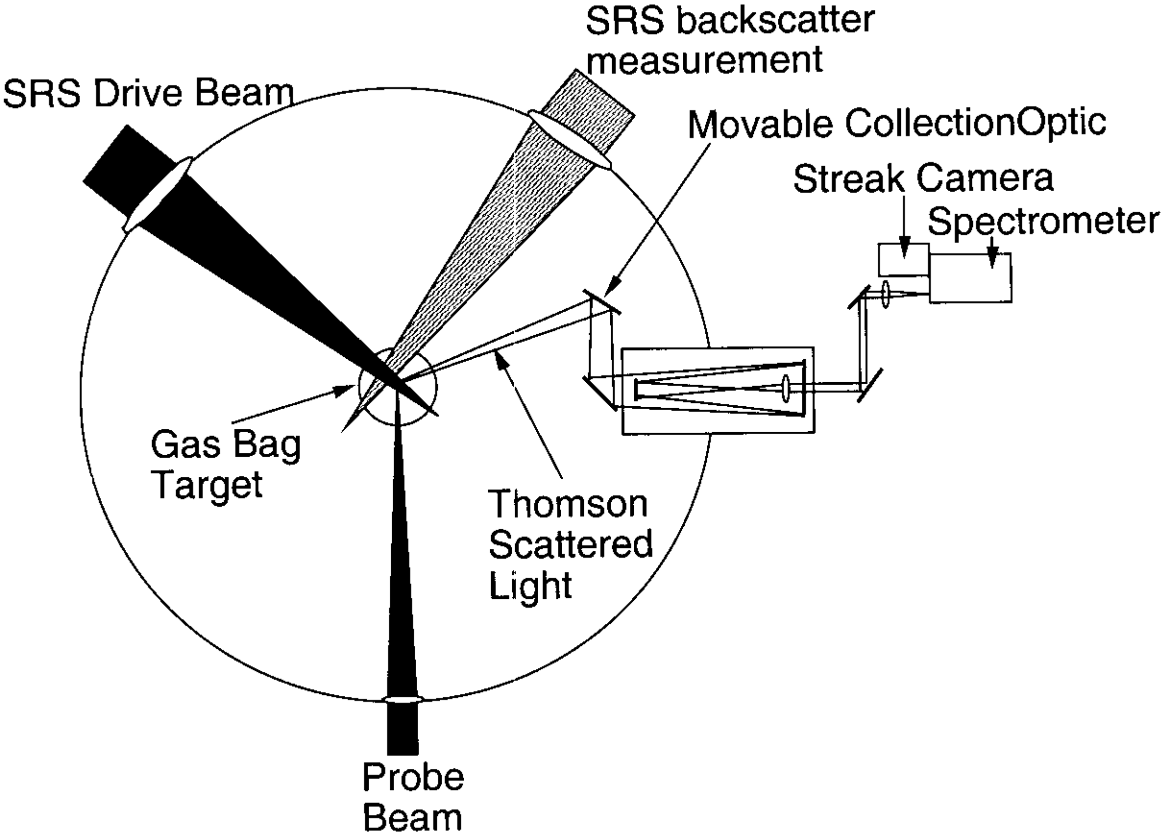
FIGURES

FIG. 1. Experimental configuration, showing SRS and Thomson Scatter Diagnostics

FIG. 2. SRS backscatter data from the LDI Experiment. Beam timing is drawn on the left side.

FIG. 3. Thomson Scatter Data showing: a) LDI Ion wave spectrum with drive beam on, b) Spectrum with drive beam off. Beam timing is drawn on the left side.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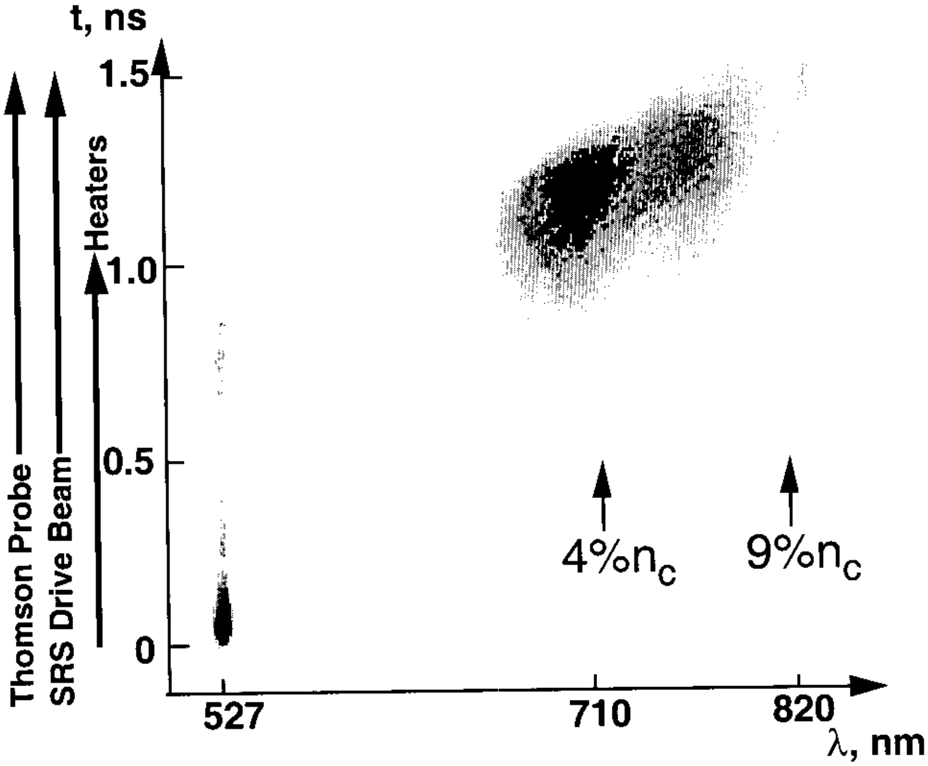
SRS Drive Beam
Movable CollectionOptic
Streak Camera
Spectrometer
Gas Bag Target
Thomson Scattered Light
Probe Beam


t, ns
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Thomson Probe
SRS Drive Beam
Heaters
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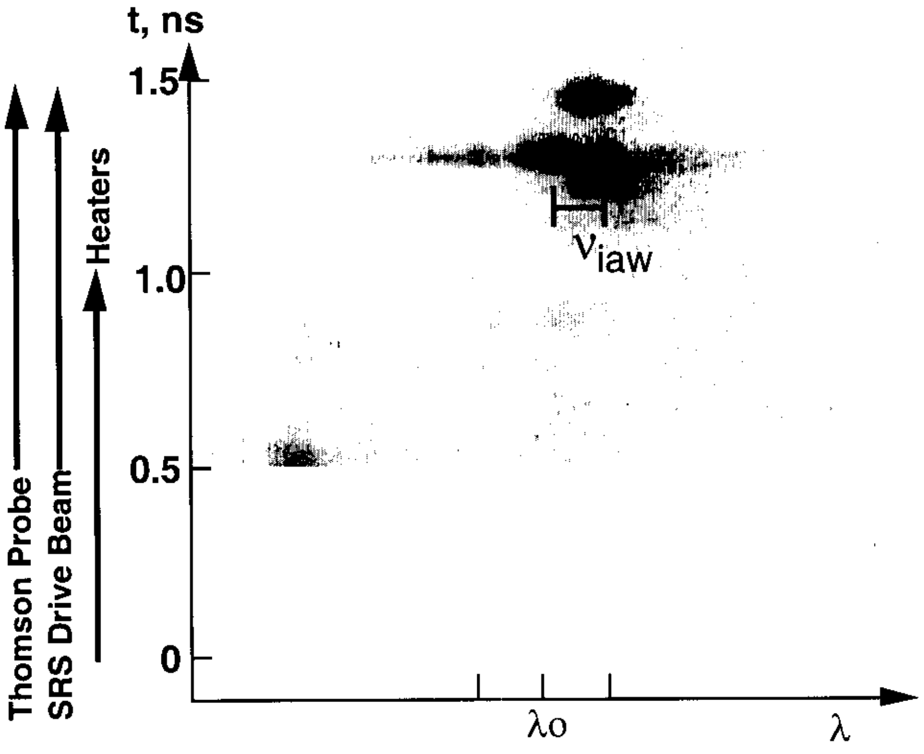
9%n_c
527
710
820
λ, nm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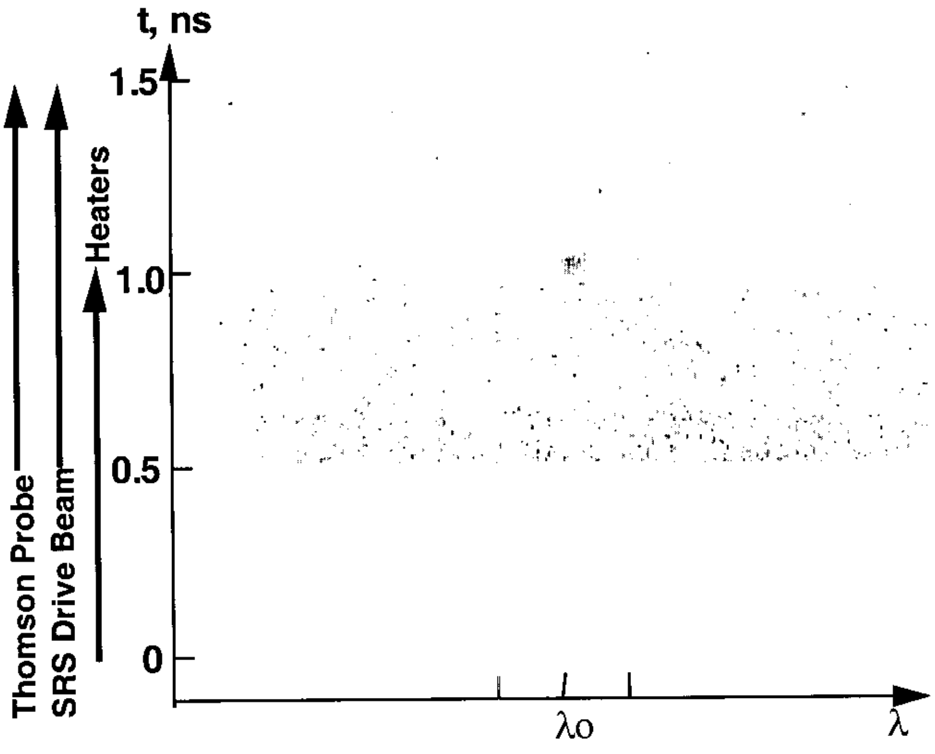
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