Laser Plasma Diagnostics

Contents

Laser produced plasmas: producing X-rays (lithography, contact microscopy), hydrodynamic experiments, ICF, calibration.

Experiments on Nova that use laser produced plasmas to generate X-rays capable of back lighting dense, cold plasmas (density = 1 to 3 gm cm-3, T = 5 to 10 eV, areal density ρ = 0.01 to 0.05 g/cm^2). X-rays used vary from 80 eV to 9 keV. Allows probing of plasmas relevant to hydrodynamic experiments. Typical diagnostics are 100 ps pinhole framing camera and time integrated CCD camera for short pulse back lighter.

Facilities available

OMEGA

(University of Rochester) A 60 beam glass laser for direct drive. Will require 1 mm diameter targets.

NIKE

(NRL) A KrFl laser for direct drive.

NIF

(LLNL) A glass laser with 1.8 MJ at third harmonic. The hohlraum is heated to about 300 eV. The radius of the central ignition hot spot is intended to be 1/36 of the original pellet radius. The hohlraum design has $r_W/r_p = 2.5$ at the equator. Targets will be about 2 mm diameter.

The fuel can be a solid or liquid D-T layer about 100 μm on the inside surface of the pellet.

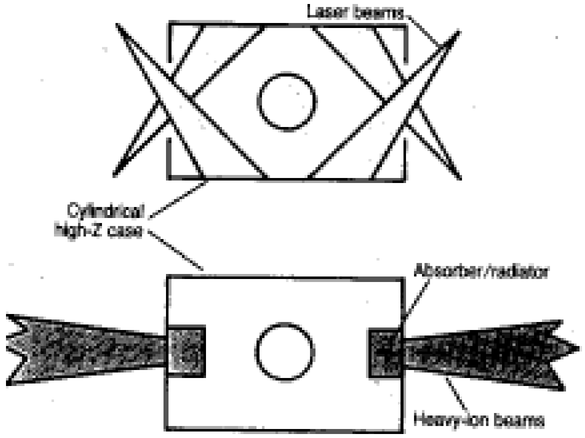
NOVA

(LLNL) The convergence is currently 25, plastic shell thickness 30 μm, pulse width 1 ns. D2 filled multiple layer shells used, about 0.5 mm diameter.

TRIDENT

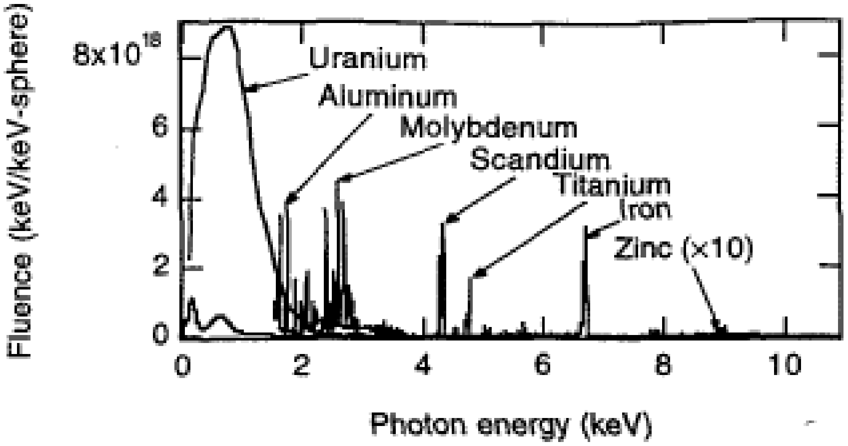
(LANL) A frequency doubled Nd glass driver (527 nm), 2 beams of up to 250 J each, for pulses of typically 80 to 2,000 ps. (50 J for a 100 ps pulse, 250 J for a 1 to 2 ns pulse). The minimum spot size is < 100 μm.

Indirect Drive



Spectra

Absolutely calibrated crystal spectrometers and X-ray diodes used to measure properties of the back lighters. Generated with incident laser radiation of $10x10^{14}$ Wcm^{-2} of 0.53 μm (green) light for 1 to 2 ns onto solid planar targets. Use uranium, aluminum, molybdenum, scandium, titanium, iron.



Need to smooth the laser beam. Use random phase plate rpp. Phase errors across the beam diameter result in large uncontrolled intensity variations. However laser beam can be divided into a large number of overlapping beamlets whose diffraction size is matched to a target. This overlap eliminates large scale spatial non uniformities at the expense of small scale interference (speckles) between the beamlets. One approach to smoothing is to introduce an RPP at the output. This has a large number of elements each of which has a phase shift of 0 or π relative to adjacent elements. The pattern of phase shifts is distributed in a quasi random manner over the surface of the plate. In addition temporal incoherence is added, then the small scale pattern moves around, resulting in a time asymptotic pattern of uniform intensity.

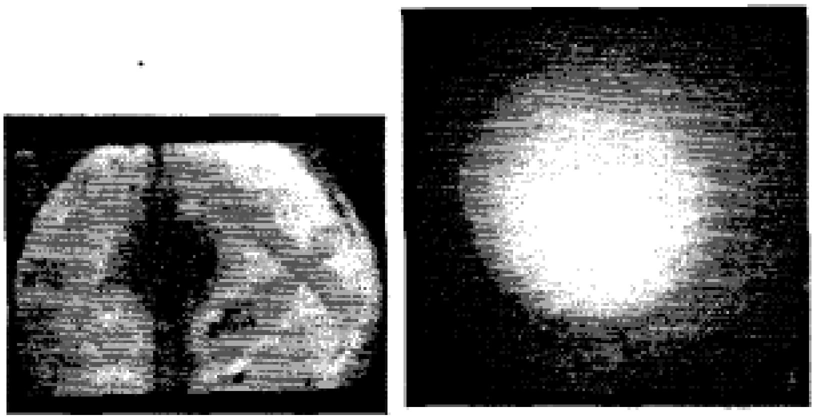


Figure 2. X-ray images of laser produced plasmas from uranium used for x-ray backlighting. The image on the left was produced by a beam without a random phase plate (RPP); structure in the laser beam reproduces in the x-ray spot. The image on the right used a RPP.

Large area back lighters.

Typically use Sc, Ti, Fe, filtered with the same element at the diagnostic to select the He-α line. A monochromatic spectrum is best, but a single line is not necessary. e.g. back lit implosion. Study Rayleigh Taylor (RT) instability, and its effects on fuel temperature, convergence, neutron yield, use dopants in ablated pusher to maintain high areal density. (dopant prevents energetic x-rays in the drive from depositing in the pusher). The pusher areal density is an important parameter. It is determined by the attenuation of the back lighter x-ray flux and compared with simulations. Witness ball: replace real target with low density ball, in which asymmetry effects are more noted. (exaggerates shock asymmetries)

Typical set up

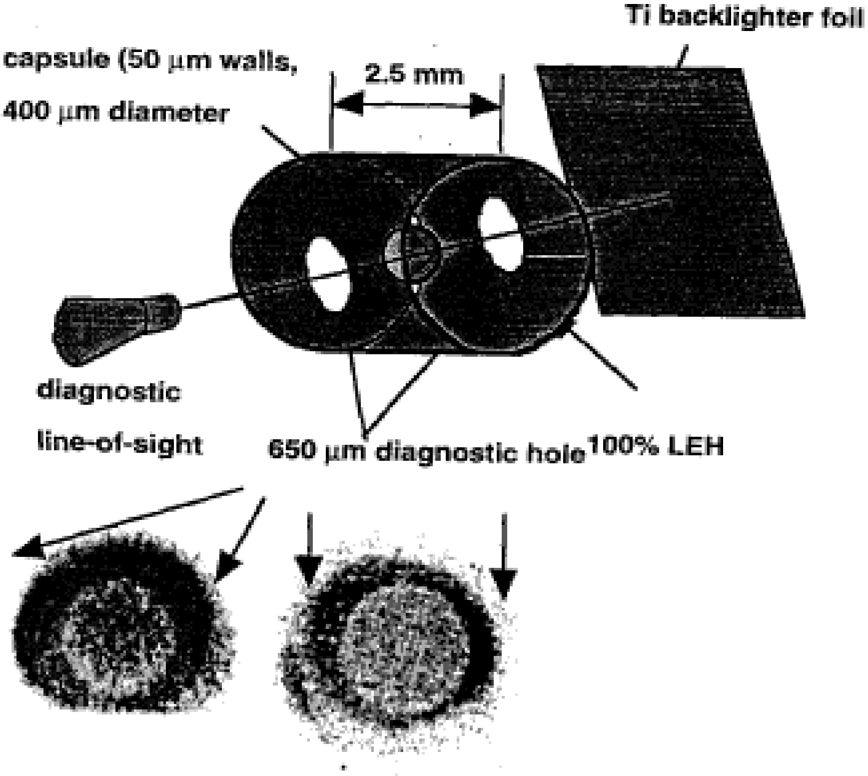
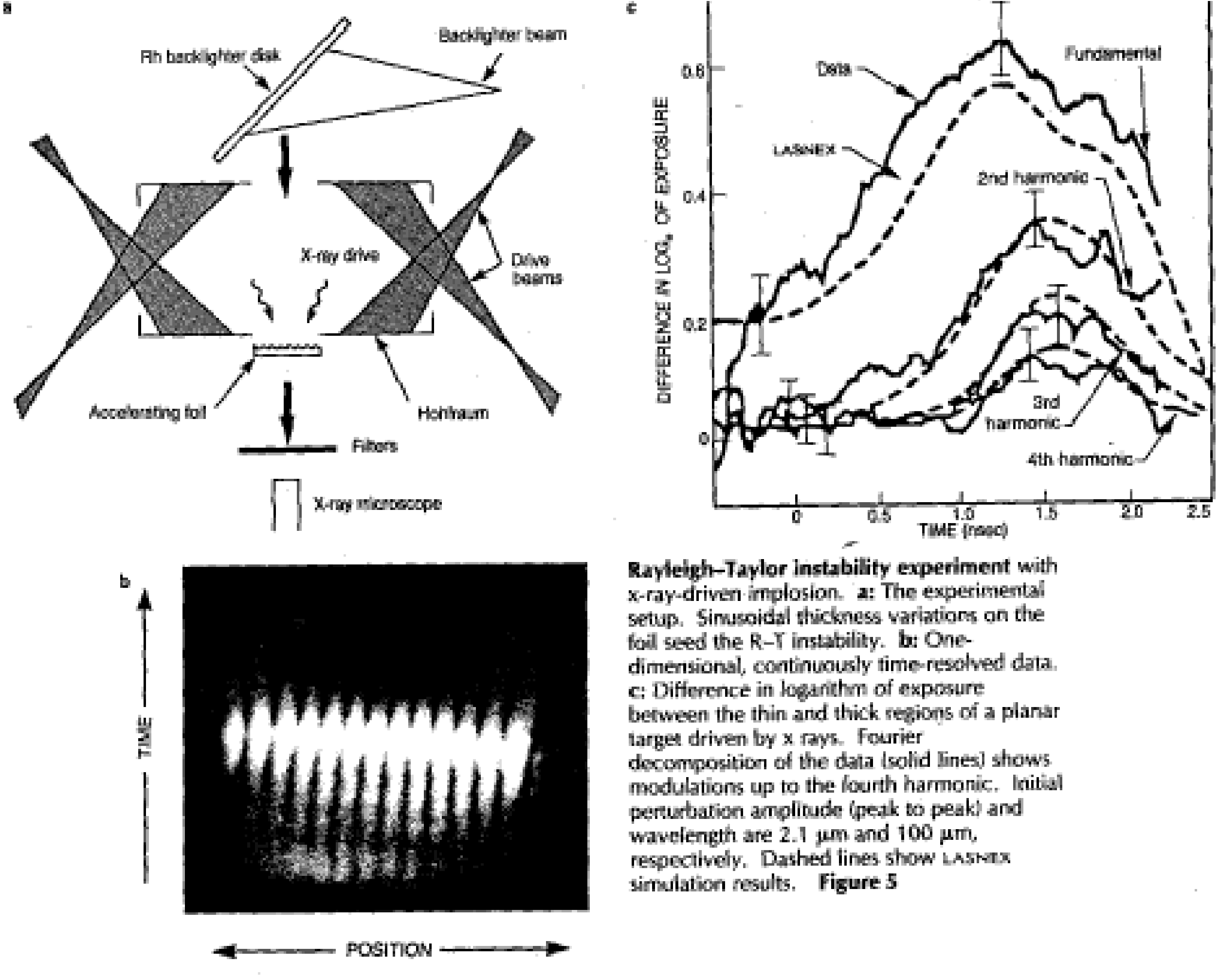


Figure 3. Experimental setup and typical images from backlit implosion and witness ball experiments. The pusher may be seen as a lighter ring (lower transmission) in the left hand image; in the image on the right a lighter ring is also visible but in this case it is due to the shock compression of the solid witness ball material. The 4.7 keV Ti He-α backlighter is essentially unattenuated by the ablated material surrounding the capsule.

Rayleigh Taylor experiments

Observable is modulation in transmission of a large area back lighter which corresponds to modulations in optical depth of a foil. As the opacity of the foil is constant to keV x-rays, the modulation represents areal density modulations. The modulation arises from sinusoidal ripples present on the surface. The foil is accelerated by the ablation and the ablation surface is RT unstable. The modulations are expected to grow exponentially, become nonlinear, and saturate. Foil can be direct or indirect drive accelerated. Use prefilter (12 µm Be) to stop X-rays below 1 keV.



Rayleigh–Taylor instability experiment with x-ray-driven implosion. **a:** The experimental setup. Sinusoidal thickness variations on the foil seed the R–T instability. **b:** One-dimensional, continuously time-resolved data. **c:** Difference in logarithm of exposure between the thin and thick regions of a planar target driven by x rays. Fourier decomposition of the data (solid lines) shows modulations up to the fourth harmonic. Initial perturbation amplitude (peak to peak) and wavelength are 2.1 μm and 100 μm, respectively. Dashed lines show LASNEX simulation results. **Figure 5**

Another example, showing modulation at the 30 μm fundamental. Structures running perpendicular to imposed perturbations are due to laser drive. Back lighter illuminates lower part of foil in first frame, progressing downward until last frame it illuminates upper part. This is an effect of parallax as the images are formed by lower and lower pinholes in the array. Hence back lighter must be large enough to overfill the area that must be illuminated when gated mcp cameras are the diagnostic.

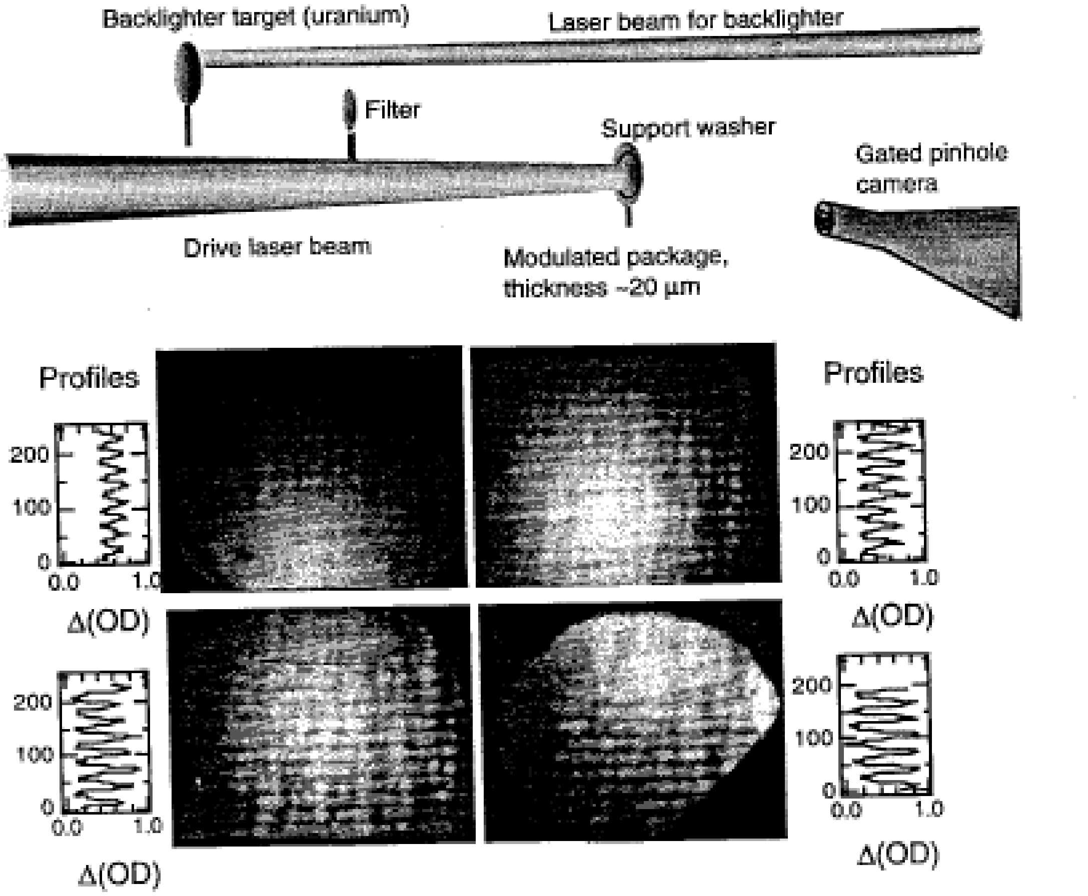


Figure 6. Experimental setup for direct-drive planar Rayleigh-Taylor experiments. The images are (left right and top to bottom) at t=1.0, 1.5, 2.0, and 2.5 ns after the start of the drive laser pulse. The size of e image is 700 µm. The initial wavelength was 30 µm and the initial amplitude 0.25 µm.

Supernova

RT is important in larger scale experiments - supernovae. These have strong density gradients and can be RT unstable. In the nonlinear regime (amplitude > wavelength) the amplitude grows at terminal bubble velocity

$$u = 0.36\sqrt{g\lambda}$$

g is acceleration of interface, λ is wavelength. Suggests a characteristic time scale

$$\tau = \frac{\lambda}{u} \approx \sqrt{\frac{\lambda}{g}}$$

Now transform from supernova to lab, so that

$$\lambda_{sn} = a_1 \lambda_{lab}$$
$$g_{sn} = a_2 g_{lab}$$

then

$$\tau_{sn} = \sqrt{\frac{a_1}{a_2}}\tau_{lab}$$

e.g. a type II 25 M_{sun} supernova, then spatial scale is 10^{10} cm, acceleration is 10^3 cm-2, time scale is 10^4 s. For lab experiment scale is 10^{-4} cm, so $a_1 = 10^{14}$. The acceleration is 10^{14} cm-2, so $a_2 = 10^{-11}$. Therefore the time scale in the lab should be $10^4/(10^{25})^{1/2}$, i.e. about 1 ns. Other parameters which would not sale (density, temperature, mode number, perturbation amplitude/wavelength, are very similar.

So you might mimic a supernova with a laser driven implosion. Need strong density gradients: use copper foil pushing a plastic layer.

Point back lighters

Use a laser produced plasma which is very small. The spatial extent of the point back lighter determines the spatial resolution. Advantages: high laser light intensity at focus means 10^{16} Wcm^{-2} and then 10 keV x-rays. uniform illumination, resolution with a fiber as the target is comparable to pinhole camera. But source size increases with time.

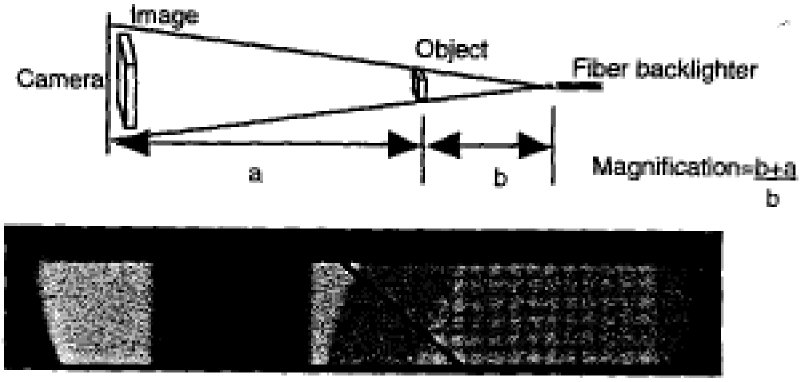


Figure 11. Point backlighter geometry and image of a resolution grid. The backlighter was a round Zn fiber 1 µm in diameter, the pulse duration was 100 ps and the magnification was 18.

Rayleigh Taylor instability

Equilibrium

$$p = \boldsymbol{j} \times \boldsymbol{B} - \rho \quad \varphi$$

use Maxwell with E constant in time so that $\times \boldsymbol{B} = \mu_0 \boldsymbol{j}$:

$$p = \boldsymbol{j} \times \boldsymbol{B} - \rho \quad \varphi = \frac{\boldsymbol{B} \cdot \quad \boldsymbol{B}}{\mu_0} - \quad \frac{B^2}{2\mu_0} - \rho \quad \varphi$$

$\boldsymbol{B} \cdot \quad \boldsymbol{B}$ tension term from curvature disappears for straight systems. the B^2 term represents stresses due to mutual repulsion of lines of force. equivalent to pressure.

Potential energy of plasma is

$$W = \int \left(\frac{B^2}{2\mu_0} + \frac{3}{2} p + \rho\varphi \right) dV$$

volume V includes any vacuum region, φ is gravitational potential. Without any dissipation the total energy is conserved (i.e. sum of W and any kinetic energy).

Let an equilibrium system be perturbed by a displacement x, a function of the initial position. To first order in x the change ∂W = 0, since this is the definition of an equilibrium. The stability is determined by the sign of ∂W(x,x), the value of ∂W keeping terms of order x^2. If ∂W(x,x) is positive the KE cannot exceed the initial value ∂W and the perturbation cannot grow. If ∂W(x,x) is negative, |∂W| and the KE can grow together as x2 increases, and we are unstable. More quantitatively

$$\frac{1}{2} \int \rho \left(\frac{dx}{dt} \right)^2 dV + \partial W(x,x) = 0$$

now let x exp(-iωt)

$$\omega^2 = \frac{\partial W(x,x)}{\frac{1}{2} \int \rho x^2 dV}$$

Thus if ∂W is negative, ω is imaginary, and the perturbation grows.

Changes to potential energy ∂W from three terms, ∂W_S at the interface, ∂W_p from deformations within the plasma, and ∂W_V, the change in magnetic energy in any vacuum regions.

Consider ∂W_S at an interface between plasma and vacuum. The plasma pressure changes discontinuously across the surface S, parallel to the lines of force.. Let x_n be the perturbation normal to the surface. The force F per unit area across the interface which is proportional to x_n. The total work done on the fluid in the course of moving x_n is

$$\delta W_S = -\frac{1}{2}\int \boldsymbol{x}_n \cdot \boldsymbol{F}(x_n)\,dS$$

In equilibrium the total pressure across the interface is

$$p + \frac{B^2}{2\mu_0}$$

As x_n increases, the pressure on the two sides of S changes in different ways, since $_n\left(p + B^2/(2\mu_0)\right)$ is different n the two sides. F(x_n) is the product of x_n times this increase in gradient as the surface is crossed in the direction of increasing x_n:

$$\delta W_S = \frac{1}{2}\int x_n^2 \left\langle \,_n\left(p + \frac{B^2}{2\mu_0}\right)\right\rangle dS$$

where <...> means the change in some quantity.

When the direction of B is everywhere the same, an instability arises if the plasma is supported by a magnetic field against the gravitational force ρ**g** per cm^3, or if the magnetic field is accelerating the plasma against the equivalent reaction force, -ρd**v**/dt. For the case of sharp interfaces, with different densities and field strengths, we can obtain the growth rate. The equilibrium equation is (see first equation, keep gravitational terms, no currents)

$$\frac{d}{dx}\left(p + \frac{B^2}{2\mu_0}\right) = -\rho g$$

The gravitational force is included: the acceleration g is directed in increasing x. Now the equation for the change in energy across the surface becomes

$$\delta W_S = -\frac{1}{2}\langle\rho\rangle g\int x_n^2\,dS$$

This is negative if density of upper layer exceeds that of lower layer. If positive x is taken in direction of **g**, then - sign in above two equations go to plus, but definition of <ρ> means this also changes sign, so we are left again with ∂W_S negative.

Choose x constant along lines of force, then no change in magnetic energy - they move as rigid rods.

Must consider change in potential energy resulting from deformations within the plasma. These will be negligible as long as wavelength is small compared to scale height ρ/gradρ. Therefore ∂W is negative if a dense plasma is supported by a lighter plasma against gravity, provided direction of B is uniform. Same is true if a lighter plasma accelerates a denser plasma by pushing it.

Unstable perturbation leads to flutes parallel to the lines of force. suppose

$$
\begin{aligned}
x_x &= Ae^{\pm kx}\sin(ky)\\
x_y &= \pm Ae^{\pm kx}\cos(ky)\\
x_z &= 0
\end{aligned}
$$

with minus above interface, plus below. Then

$$\omega^2 = -gk\frac{\langle\rho\rangle}{2\bar{\rho}}$$

where $\langle\rho\rangle$ is jump in ρ, $\bar{\rho}$ is average across the surface.

Femto-second laser produced plasmas

High intensity short pulse lasers produce ultra short x-ray pulses. 1981: 1 ns $C0_2$ laser at kJ level showed that potential at focus produced superhot electrons which when incident on solid target produced bremsstrahlung In 1992 Kmetec reported similar results with 125 fs 40 m, 5 Hz pulse. Laser pulse absorption and x-ray conversion efficiency are determined by wavelength of laser, irradience, polarization, angle of incidence. These govern the temporal behavior and spatial gradients of plasma electron temperature and density and gradients. Solid targets absorb laser power over a skin depth (100A, and in heated region Te about 100 to 1000 eV. Thermal X-rays about 1 keV and above are produced. . Strong gradient and high density means that rapid quenching of x-rays occur by thermal conduction into underlying cold material and hydrodynamic expansion. Besides collisional absorption, resonance and non- collisional absorption matter. These nonlinear processes give bremsstrahlung radiation and Kα from target.