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The Petawatt Laser - Physics Today Article

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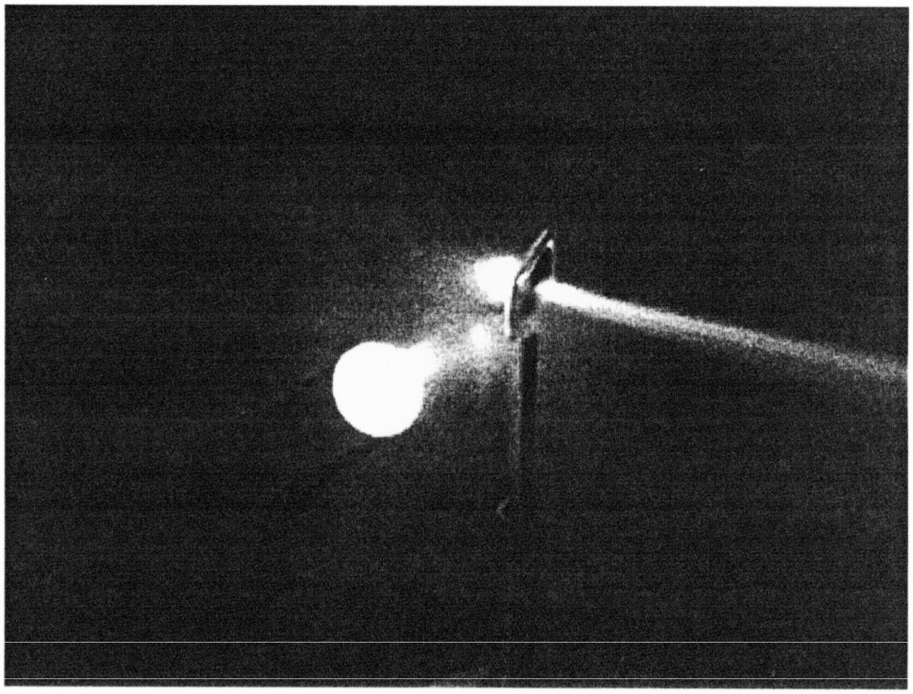

Cover Art: Photographic image of single beam target experiment with the Petawatt Laser. The laser pulse is entering from left. The background green light is the result of second harmonic emission from the target. Particles emerging from the back of the target can be observed in a series of jets at right.

The development of small scale multiterawatt and now petawatt lasers has opened an entirely new regime of laser matter interaction to exploration.[1] Applications of these lasers range from enabling new accelerator concepts[2] to new approaches to inertial confinement fusion (ICF). In 1992, we embarked on a project to develop a laser capable of producing petawatt pulses in order to examine the fast ignitor concept for inertial confinement fusion.[3] Shown schematically in fig. 1, this application requires high pulse energy in addition to the short pulse duration. The essential idea is to pre-implode a deuterium-tritium capsule to an isochoric (uniform density) condition. At the point of maximum compression, irradiate the side of the imploded core with a laser pulse much shorter than the hydrodynamic disassembly time of the irradiated spot ($\tau \approx R_{spot}/v_s \leq 10$ psec). Hot electrons (200 keV<E<1 MeV) generated by the interaction of the intense (10^{19} - 10^{21} W/cm^2) light with plasma rapidly equilibrate in the dense fuel. The energy equilibration of the electrons raises the overall ion temperature to 5-20 keV initiating fusion burn. High laser pulse energy is required in order to produce enough hot electrons to heat a sufficient number of ions to initiate a self-sustaining fusion burn. In addition, nearly perfect beam quality is required in the laser in order to achieve a small spark region. The Fast Ignitor concept offers the possibility of high target gain at reduced total drive energy than conventional ICF. However, unlike conventional ICF, this approach relies on untested physics in a completely new regime of laser-matter interaction.

To meet the conditions necessary to address the numerous issues associated with the Fast Ignitor *and* serve as a general facility for experiments in intense laser matter-interaction, the Petawatt laser was designed to produce 1 kJ pulses with a pulse duration adjustable between 0.4 and 20 ps and sufficient beam quality to produce an irradiance greater than 10^{21} W/cm^2 when focused at f/3. This design called for a hybrid Ti:sapphire/Nd:Glass laser system in order to provide sufficient bandwidth to achieve the shortest pulse durations, large scale diffraction gratings to compress the pulse after amplification, compression in vacuum in order to avoid beam distortion and self-phase modulation resulting from the nonlinear refractive of air and be engineered for routine operation and high levels of reproducibility and reliability. The laser system begins with a standard Kerr-lens mode-locked Ti:sapphire oscillator producing 105 fsec pulses at 1054 nm. A single pulse is selected from the mode-locked train and stretched to ≈3 nsec prior to amplification. This pulse is amplified to 6-7 mJ in a linear Ti:sapphire regenerative amplifier and further amplified to 50 mJ in a ring-regenerative amplifier. These Ti:sapphire amplifiers are designed to be dynamically stable TEM_{00} cavities with both Kerr and thermal lensing and produce a gain of over 10^8 with no gain narrowing.[4] Further amplification in mixed phosphate glass rod amplifiers produces a spectrally-shaped pulse up to 12 J in energy.[5]

This pulse is further amplified up to a maximum of 1300 J by a series of disk amplifiers. Near diffraction-limited beam quality is achieved by limiting the beam to the central 80% of these amplifiers. Gain narrowing in the phosphate glass amplifiers reduces the spectral width to 4.0 nm and reduces the pulse duration to 800 psec. Additional energy could be extracted from the disk amplifier section but at the price of degraded spatial quality and temporal contrast upon recompression.[6] These effects result from the accumulated nonlinear phase, B(**r**,t),

$$B(\mathbf{r},t) = \frac{2\pi}{\lambda} \int n_2 |E(\mathbf{r},t)|^2 \, dz \qquad (1)$$

where the integration is performed over the optical path length through the laser system, n_2 is the nonlinear refractive index of the material, and E(**r**,t) is the spatially and temporally dependent electric field. As an example, a laser pulse propagating through 10 cm of fused silica at a power density of 10 GW/cm^2 accumulates 2 radians of nonlinear phase. The technique of chirped-pulse amplification was developed specifically to overcome the limitations imposed by this nonlinear phase by stretching the pulse prior to amplification thereby reducing the peak power in the amplifiers. However, economic factors dictate that petawatt class lasers will almost always be operated at the maximum B-integral allowable in the laser system even with chirped-pulse amplification. A good rule of thumb for most relay imaged laser system is to limit the accumulated nonlinear phase to less than 2 radians. This is a result of the well known degradation of spatial beam quality due to wavefront distortion. Small scale self-focusing causes distortion in the phasefront of the beam which results in decreased focusability or, in severe cases, beam filamentation and damage.

Another effect of the nonlinear phase is self-phase modulation (SPM). This effect is easily observable with ultrashort-pulses by observing the increase in bandwidth of an intense laser pulse upon passage through a nonlinear medium according to,

$$\omega = \omega_o - \frac{\partial B}{\partial t}$$

Spatial phase modulation is determined by the value of the nonlinear phase while frequency modulation is determined by the time-derivative. For a conventional (near transform-limited) laser pulse with the duration equal to the stretched pulse in a petawatt class laser (≈500-1000 psec), the self-phase modulation effect would be negligible. However, the pulse in these system is strongly-chirped (i.e., exhibits a time-dependent frequency). As a result, the central part of the pulse (near the carrier frequency) experiences a greater phase retardation than the early or later part of the pulse where the intensity is less. This limits the ability to recompress the pulse and often results in temporal wings appearing on either side of the compressed pulse.[6]

Following amplification, the chirped pulse is compressed to a pulse duration which can easily be adjusted from 0.43 to 30 ps. Pulse compression occurs in vacuum with a pair of large aperture diffraction gratings arranged in a single pass geometry and a compressor throughput of 84% (figure 2). In most CPA systems the beam ellipticity and spatial chirp associated with a single-pass compressor geometry would be intolerable. However, in the limit that the diameter of the beam is much larger than the dispersed length, these effects are negligible. Currently, the Petawatt operates with a 46 cm beam and a dispersion length of

$c\tau_{str} * \cos\theta_{compressor} \approx 20$ cm. This system is limited to a maximum pulse energy of 650 due to the use of sub-aperture (75 cm) diffraction gratings. These gratings exhibit a diffraction efficiency of 95%, a diffracted wavefront quality of better than 0.08 micron (peak to valley) and a damage threshold of 0.42 J/cm^2 for 1054 nm pulses at 200 fsec.[7] Development of gratings of this size, wavefront quality, efficiency and damage threshold was one of the enabling technologies required to achieve petawatt pulses. These gratings will be increased to the full 94 cm size in July of 1997 and thereby allow operation of the petawatt at $\approx$1 kJ with a 58 cm diameter beam.

Most CPA laser systems are designed to produce the minimum pulse duration upon recompression. This is accomplished by setting the compressor to cancel the dispersion of the stretcher and material. Since the compressor cannot cancel the dispersion of the stretcher and material in the laser system exactly, the system is designed to minimize the residual phase, $\delta = \phi_{com}(\omega) + [\phi_{str}(\omega) + \phi_{mat}(z,\omega)] = 0$. These phase functions are often written in a Taylor series expansion,

$$\phi_{mat}(z,\omega) = \beta_1(\omega-\omega_o)\, z + \frac{\beta_2}{2!}(\omega-\omega_o)^2 z + \frac{\beta_3}{3!}(\omega-\omega_o)^3 z + \frac{\beta_4}{4!}(\omega-\omega_o)^4 z + \ldots$$

where $\beta_n = [\partial^n k/\partial\omega^n]_{\omega=\omega_o}$. The stretcher/compressor combination in the Petawatt laser are designed to correct for chromatic aberration and material dispersion in the system up to third-order (i.e., only the fourth-order terms in δ remain). This is sufficient for pulses of duration greater than 100 fsec. Output pulse characteristics of the petawatt beam under current operational conditions are shown in figure 3. The fine scale structure in this figure is the result of individual elements of the CCD array used to record the spectra and autocorrelation.

Target experiments with petawatt pulses are possible either in an independent target chamber or with the Nova laser system for integrated fast ignition. Focusing the beam is accomplished using an on-axis parabolic mirror alone, or in conjunction with a secondary "plasma" mirror, as shown in Fig. 4.[8] For irradiances > 10^{14} W/cm^2, short pulse radiation creates a critical density plasma on the surface of a dielectric substrate, with a reflectivity approaching 95% (fig. 4b). For incident pulses on the order of 500 fs, the plasma has insufficient time to undergo hydrodynamic expansion, producing a reflected wavefront comparable to the original optical surface. This novel targeting system enables the production of high contrast pulses, with an easily varied effective focal length as well as off-axis experiments.

Successful completion of the Petawatt laser was enabled by the contributions of many people at LLNL. Particular thanks are owed to J.A. Britten, R. Boyd, C. Brown, S. Herman, J.L. Miller, W. Olsen, D. Pennington, B.W. Shore, B.C. Stuart, G. Tietbohl and M. Vergino.

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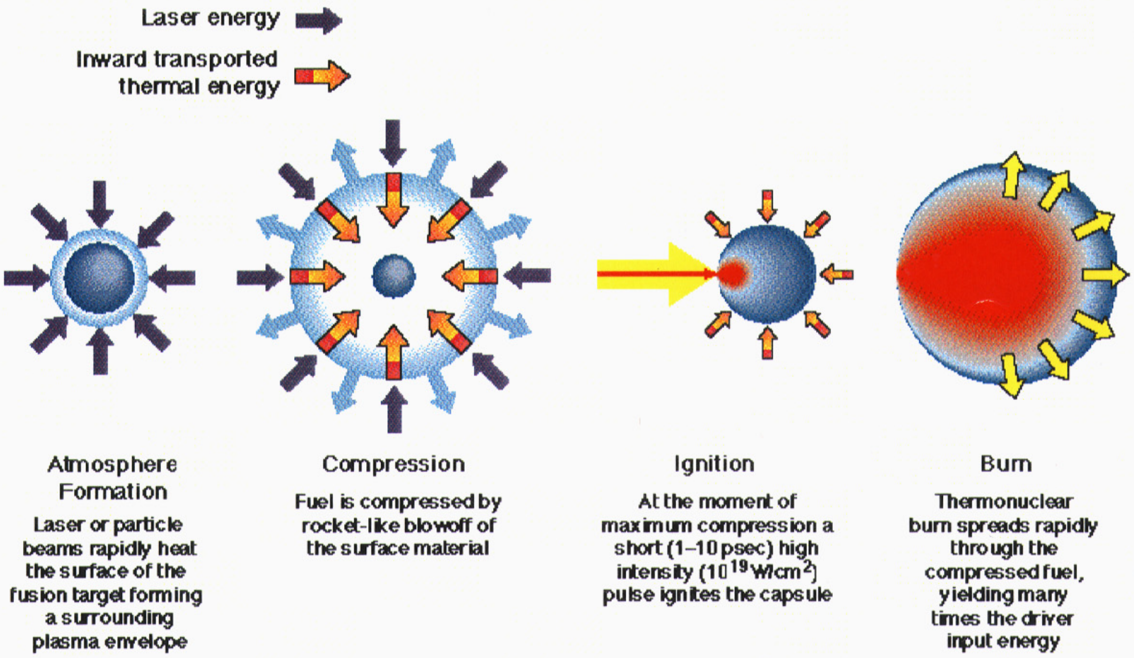


Figure 1: Diagram of Fast Ignition concept in inertial confinement fusion

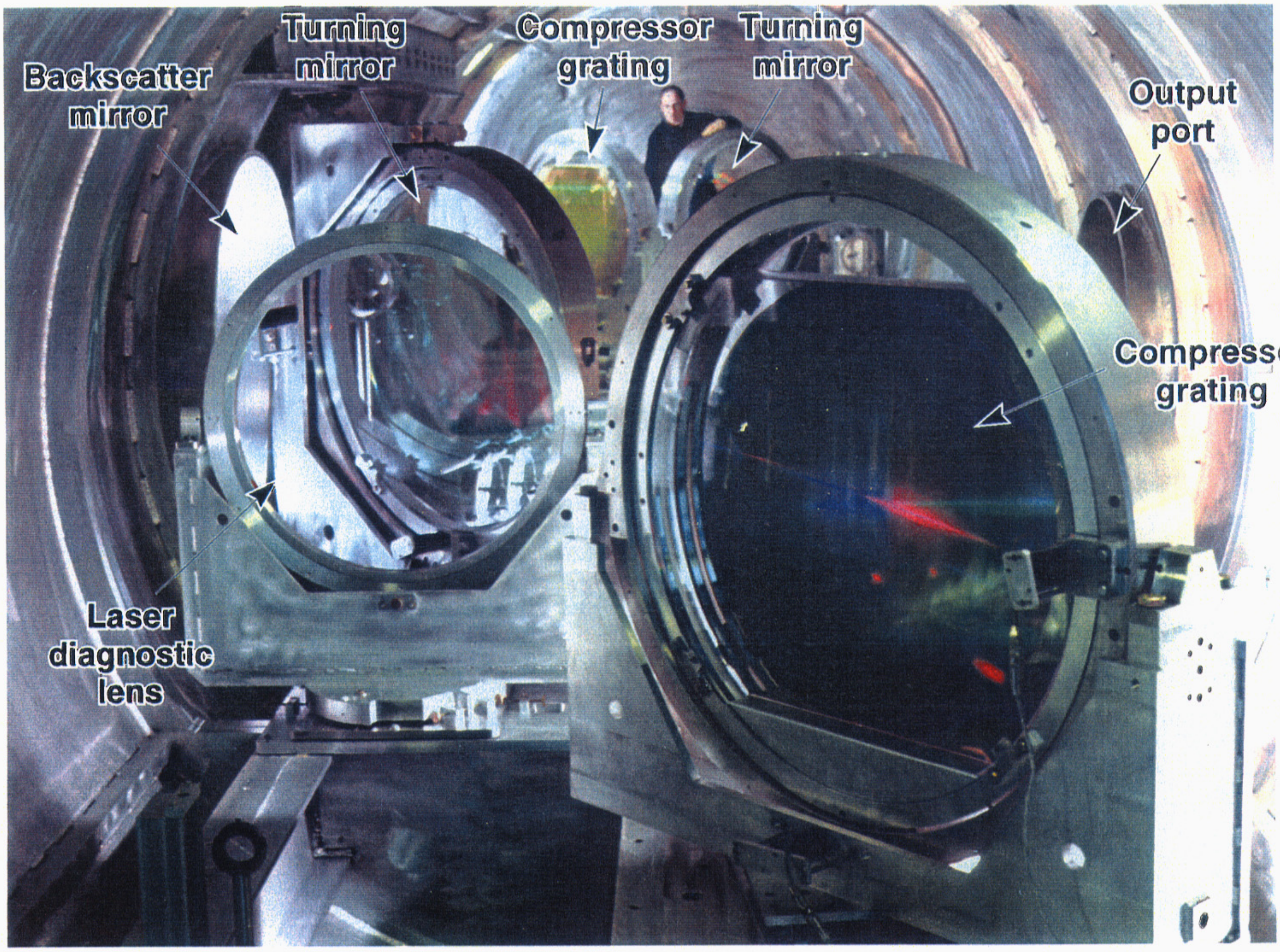
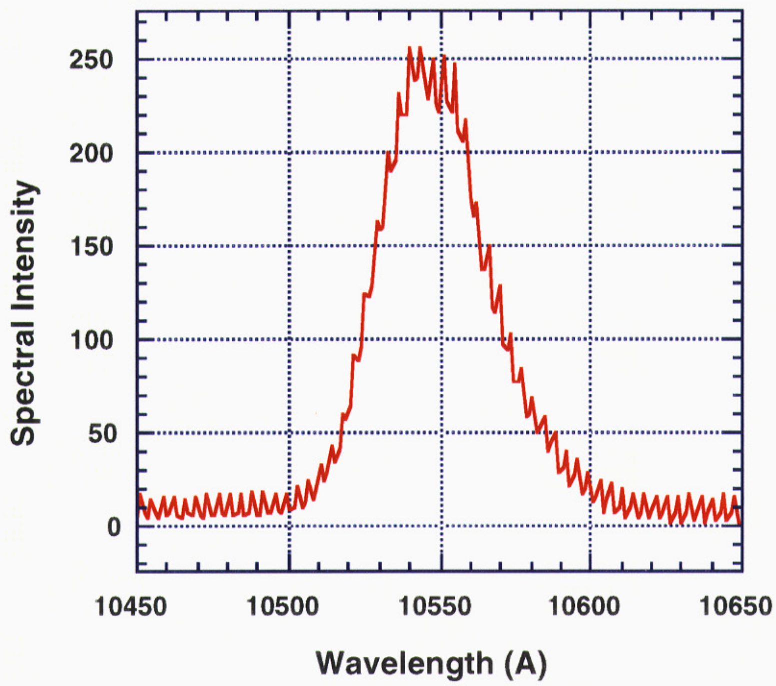


Figure 2: View inside the Petawatt Compressor Chamber



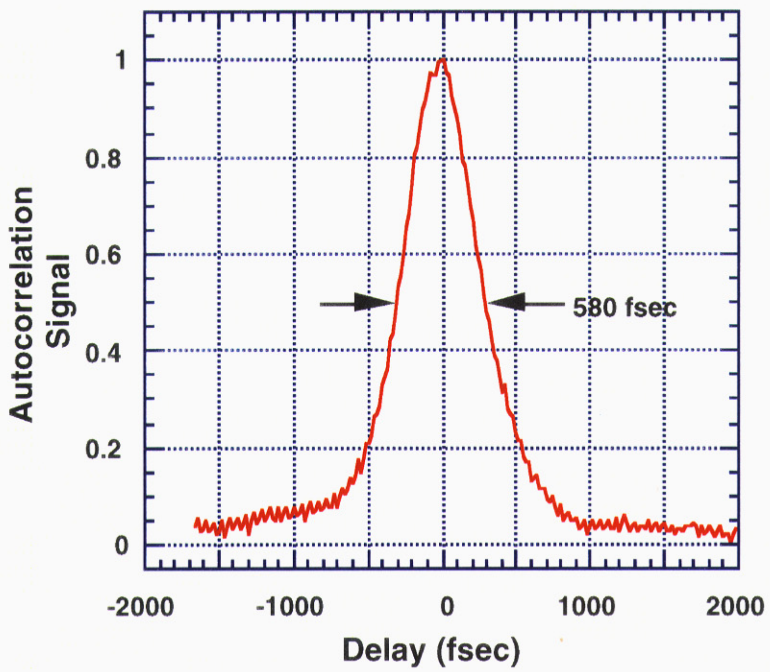
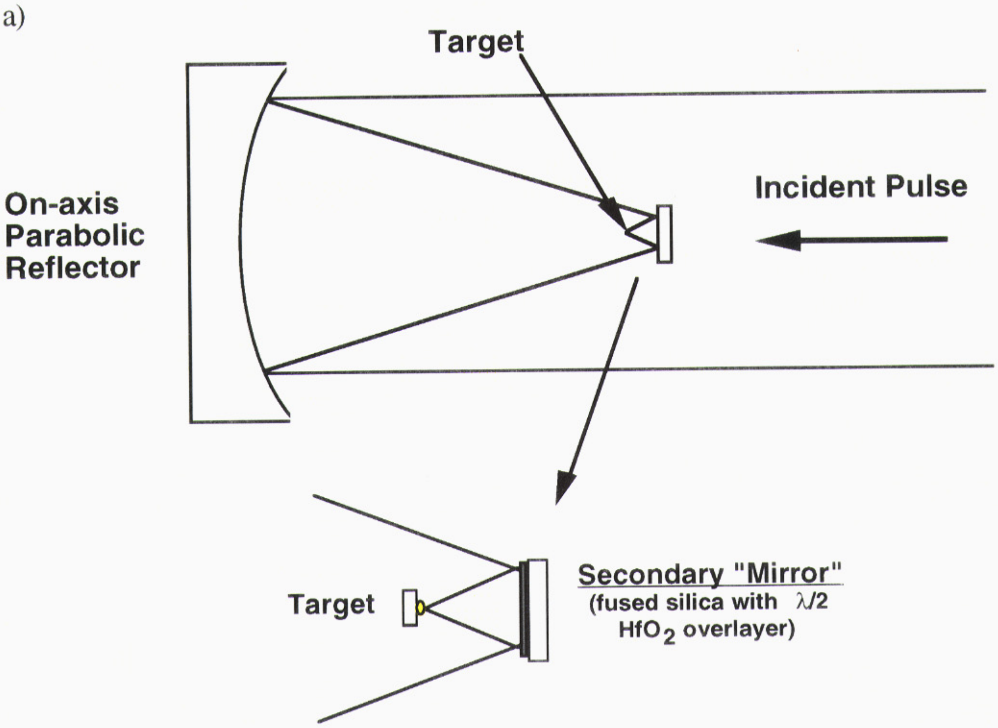


Figure 3: Measured pulse parameters in the first Petawatt shot series (May 1996) at an energy of 620 J. a) Near-field beam profile, b) pulse spectrum and c) auto-correlation (deconvolved pulsewidth =420 fsec), $\Delta\upsilon\Delta\tau = 0.43$.

a)



b)

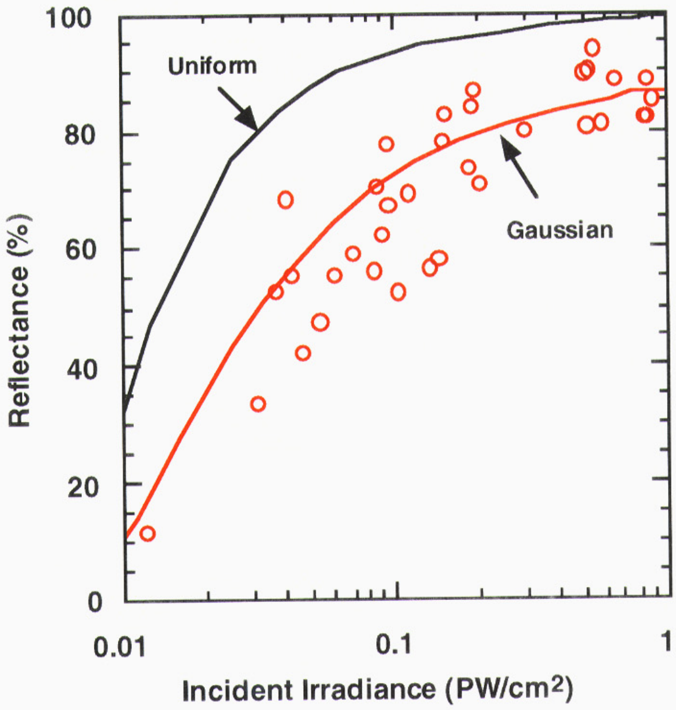


Fig. 4: a) Cassegranian focusing concept using a plasma for the secondary mirror.
b) Measured reflectivity from the plasma mirror

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