CONSIGLIO NAZIONALE DELLE RICERCHE
Istituto di Fisica Atomica e Molecolare

Experiments on Ultrashort, Ultraintense Laser Interaction with Thin Foils

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OUTLINE

- **Introduction: CPA pulse features and laser-solid interactions**
- **Interactions with thin foils**
- **Absorption and X-ray emission in steep density gradients**
- **High intensity interactions with highly over-dense plasmas**
- **Instabilities and acceleration in long scale-length plasmas**
- **Perspectives and future work**
- **Acknowledgements**

PREPULSE PROBLEM

- **CPA lasers are usually characterised by three different timescales of intensities:**

  > Amplified Spontaneous Emission (ASE) in the nanosecond timescale

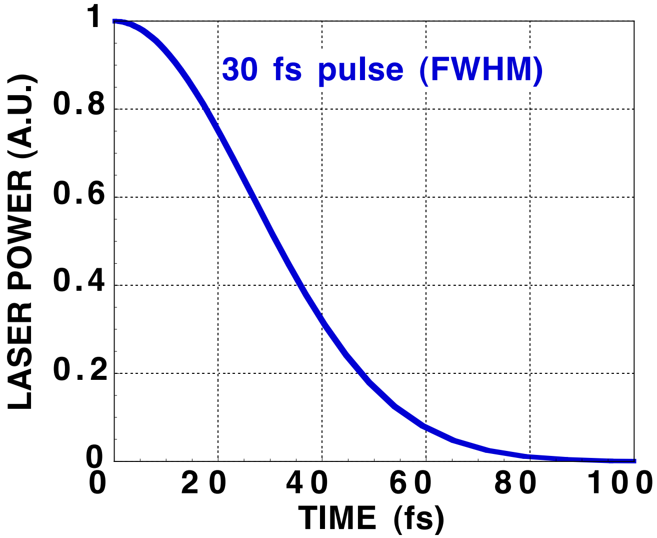
  > Imperfect compression of the chirped-amplified pulse: picosecond timescale

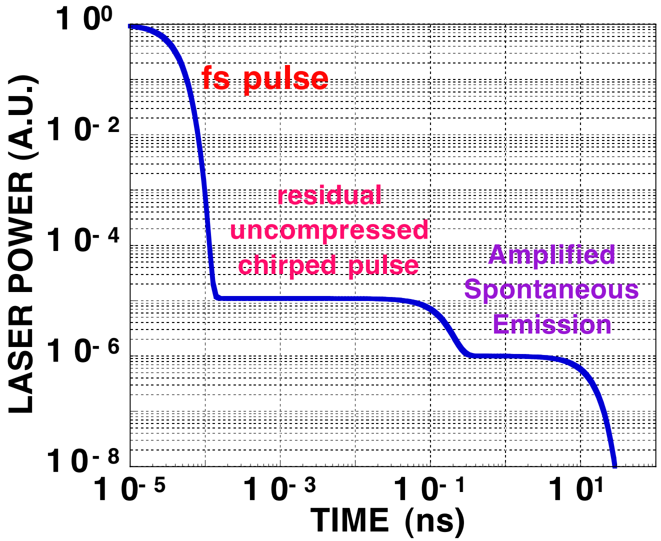
  > Compressed pulse (main pulse): femtosecond timescale

- The intensity of ASE on target must be compared with the intensity threshold for plasma formation on the target.

TYPICAL LASER PULSE DYNAMICS

The type of interaction of ultra-intense pulses with thin-foils depends critically upon the laser-pulse features on a large dynamic range





- Contrast ratio (CPA power/ASE power) for TiSa lasers tipically smaller than to 10^7
- Available ultrashort (<<1ps) CPA focused intensities on target 10^{20} W/cm^2
- ASE intensity on target can exceed plasma formation threshold for most solid targets

TARGETS: WHY USING THIN FOILS

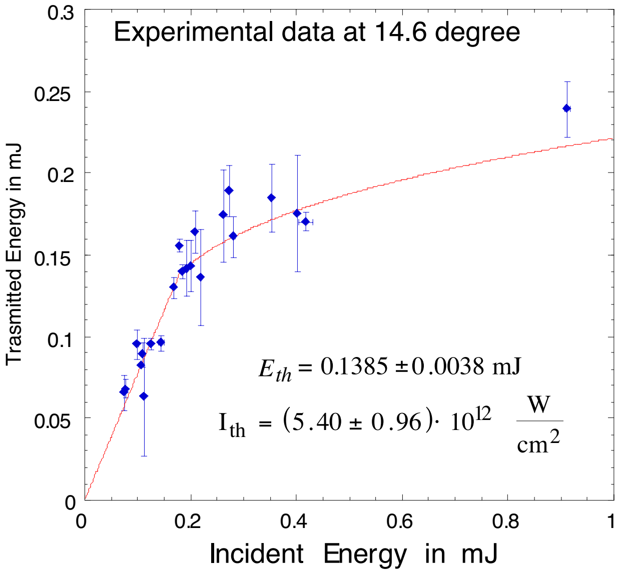
We use self-supported thin plastic (FORMVAR:$C_5H_{11}O_2$) foil targets with thickness ranging from 0.08μm up to 3μm

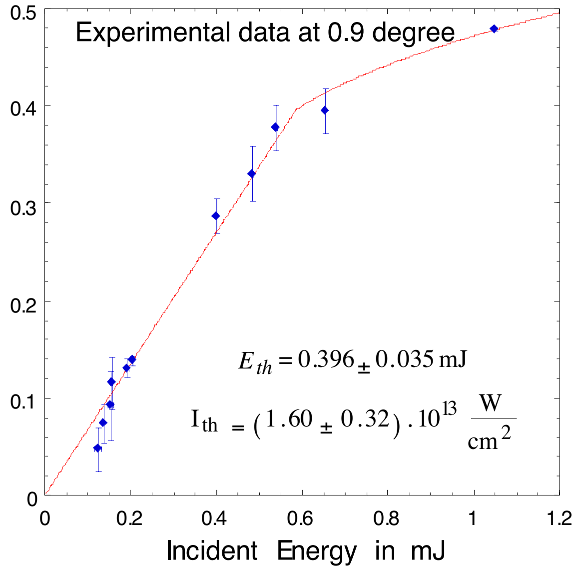
- Thin dielectric foils have been found to exhibit high damage thresholds
- Optical transparency enables volume laser propagation prior to breakdown
- Forward emission (ω,e^-,X, γ etc.) in laser-solid interactions propagates freely
- Planar symmetry enables optical diagnostics on transmission/reflection
- Exploding foil technique is well established as plasma pre-forming technique
- Smooth long-scalelength plasmas can be easily generated and characterised*
- Peak plasma density above critical density can be achieved

*See L.A.Gizzi et al., Phys. Rev. E **49** 5628 (1994); M.Borghesi et al., Phys. Rev E **54** 6769 (1996)

THIN FOIL ps PLASMA FORMATION THRESHOLD

The experimental investigation* was performed using a Nd-YAG laser with well characterised spatial and temporal profiles





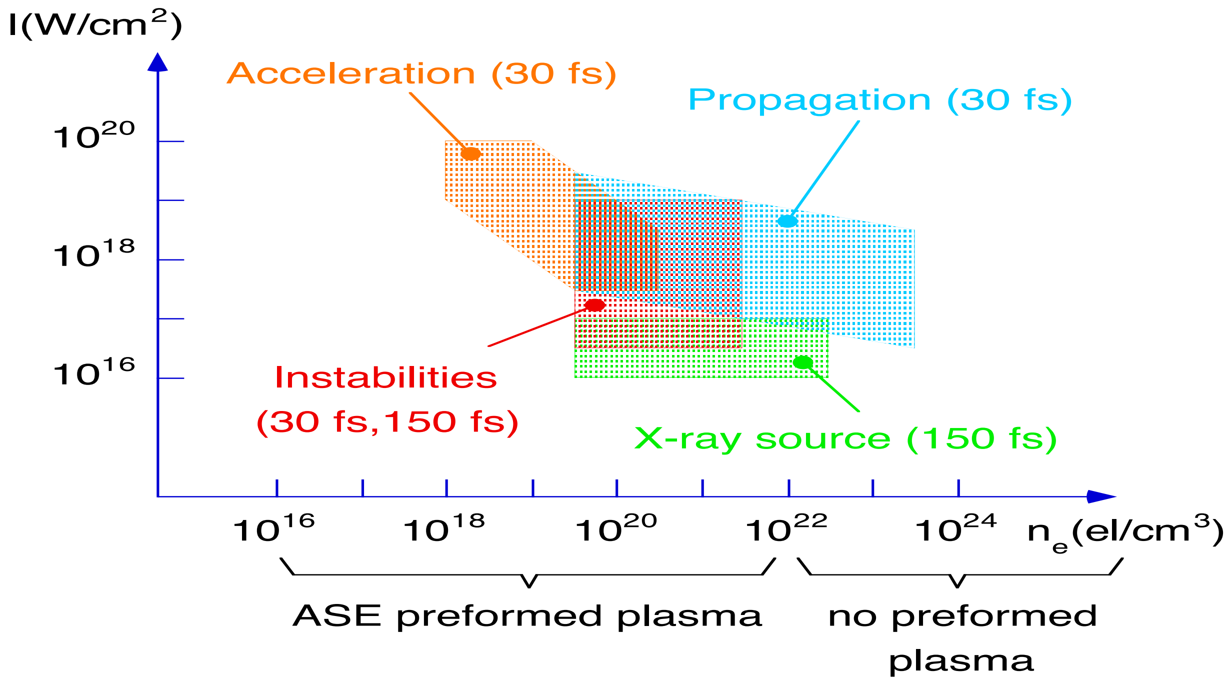
Experimental data are well fitted by a simple 2D analytical model based upon local transmissivity-ionisation-reflectivity and accounts for the actual laser intensity distribution on target

- ps PFT decreases with the angle of incidence; $I_{th@14.6^\circ} = 5.4 \times 10^{12}$ W/cm^2
- Lower threshold has been measured for ns pulses (ASE time-scale).

*See M.Galimberti et al., Laser & Par. Beams (2000), in press

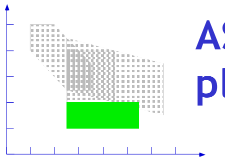
EXPLORED INTENSITY-DENSITY SPACE

Interaction conditions and dominating physical mechanisms can be identified schematically by a region in the intensity/density space

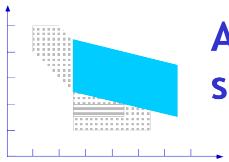


OVERVIEW OF fs EXPERIMENTS

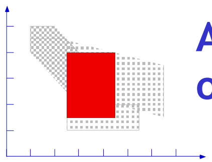
Interaction conditions explored experimentally



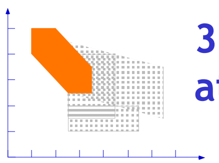
ASE intensity on target is below the plasma formation threshold and plasma scale-length is set by the ps pedestal.
Important issues: absorption and X-ray generation;



ASE is below the plasma formation threshold and fs interaction with the solid target occurs.
Important issues: fast ionisation and overdense propagation



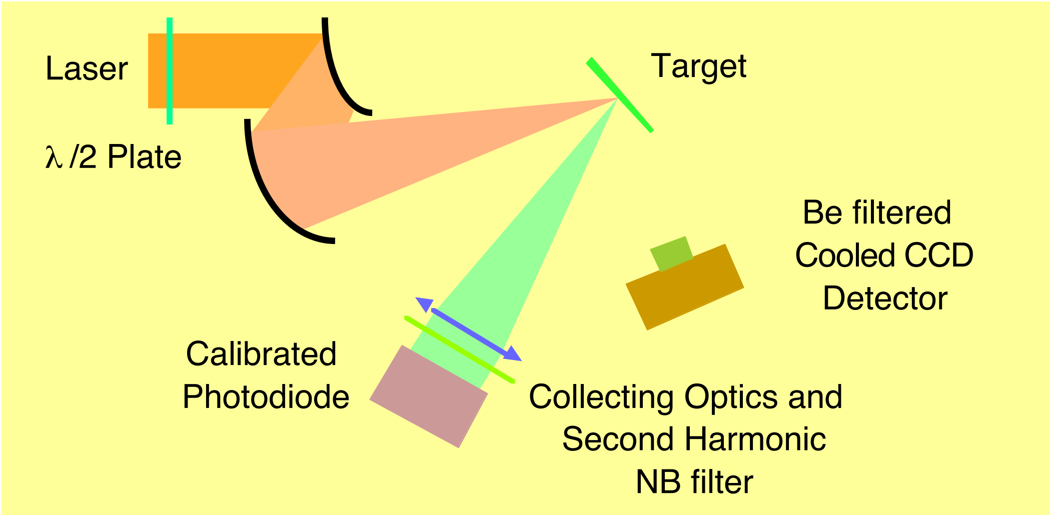
ASE produces a premature plasma formation well before the arrival of the main pulse on the target.
Important issues: instabilities



30 fs laser pulse interacts with an ASE-generated underdense plasma at ultra-relativistic intensities (10^{20} W/cm^2)
Important issues: acceleration of electrons

X-RAY SOURCE (150 fs)

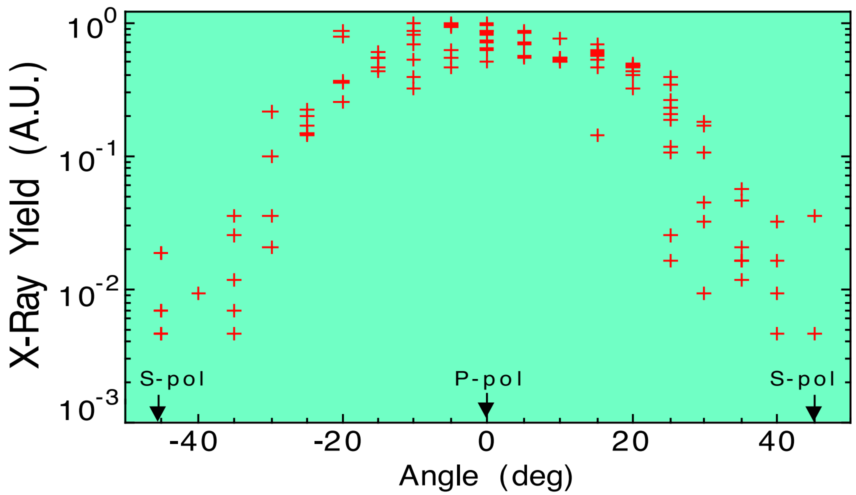
150fs pulses focused at an intensity of 5×10^{17} W/cm^2 on 0.08 μm thick plastic foils

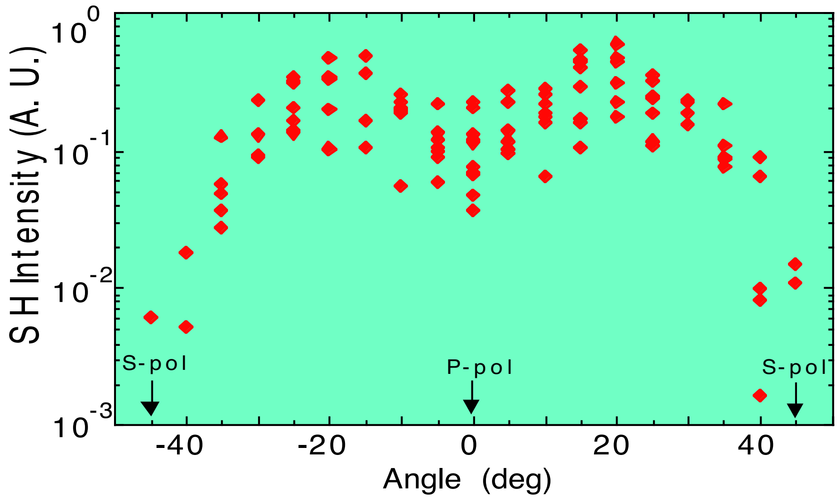


- **Laser polarisation varied from *s* to *p* using a λ/2 wave plate**

INTERACTION VS. POLARISATION

What we detect: X-rays and specular second harmonic emission





Stronger laser-target coupling is found in *p*-polarisation*.

Maximum X-ray emission occurs in conditions of *p*-polarization

The X-ray spectrum shows high energy photons up to several tens of keV.

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*See L.A.Gizzi et al. Phys. Rev. Lett. **76**, 2278 (1996)

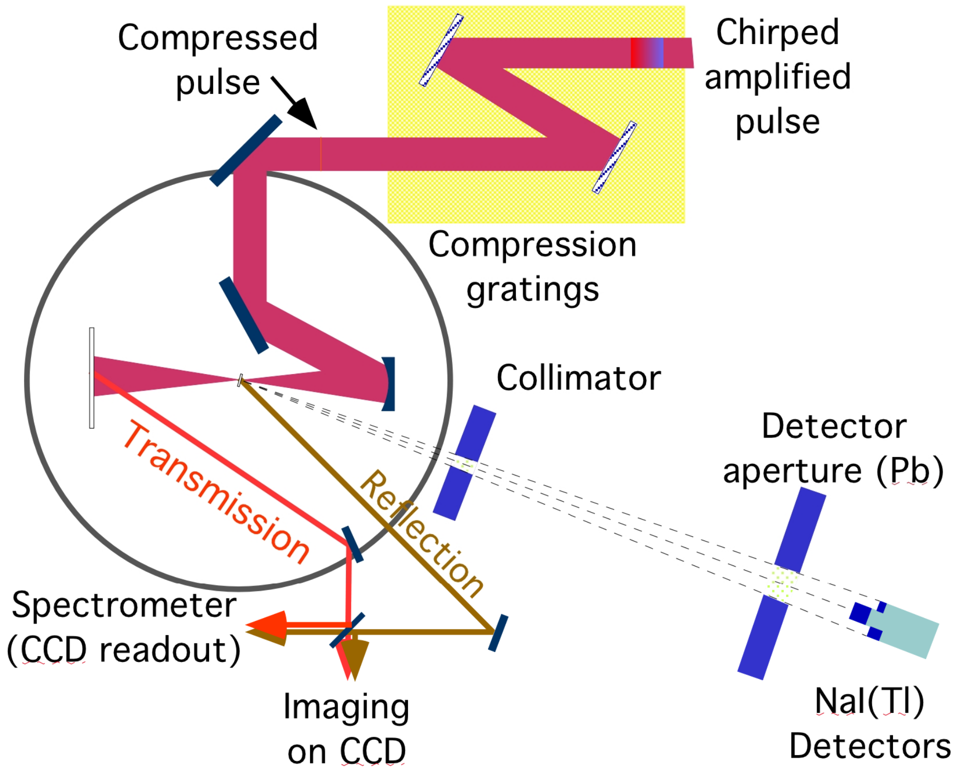
LOW *ASE* EXPERIMENT RESULTS

- **No premature plasma formation occurs using thin targets.**
- **Energy coupling is strongly polarisation dependent**
- **Resonance absorption takes place at the critical density**
- **Second harmonic emission and hard X-ray emission are correlated**
- **Possibility of controlling the X-ray source via laser polarisation**

Next step: SHORTER PULSE and HIGHER INTENSITY ON TARGET

LOW *ASE* - SHORTER PULSE (30 fs)

30 fs laser pulses focused on 0.1μm and 1μm plastic foils.

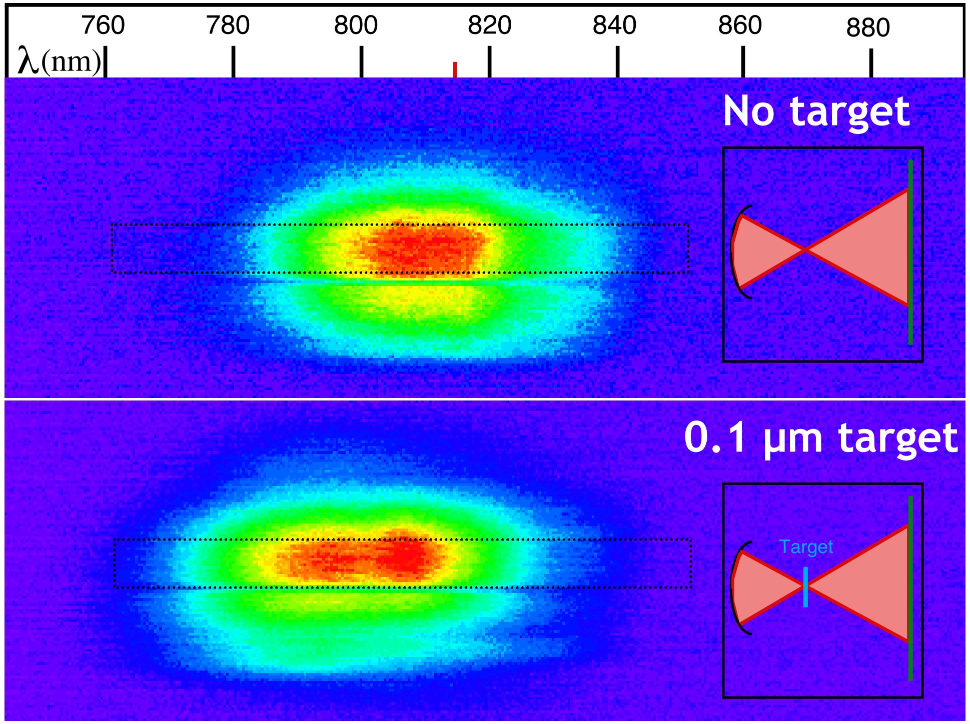


What we detect:

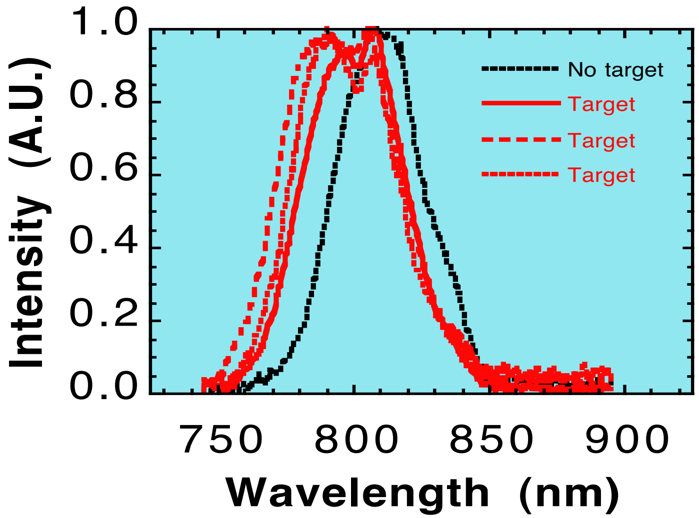
- Spectrum, intensity and image of transmission and reflection
- Second harmonic emission
- 3/2 ω_L emission
- Collimated γ-ray emission
- Diffused γ -ray emission

ULTRA-FAST IONISATION

The spectrum of transmitted laser light is blue-shifted



Lineouts of spectra with and without target at 4×10^{17}W/cm^2



ULTRA-FAST IONISATION - 2

Blue-shift is interpreted as a signature of ultra-fast ionisation

ionisation ⇒ change of refractive index ⇒ self-phase modulation

$$\delta\omega = -\frac{\omega_0}{c} L \frac{d\,\mu(t)}{d\,t} \approx -\frac{\omega_0}{c} L \frac{\Delta\,\mu(t)}{\Delta\,t}$$

The measured blue-shift gives the timescale of ionisation processes

$$L = 0.1\ \mu\text{m} \Rightarrow \Delta\mu = -1 \Rightarrow$$

Intensity on target = $5\text{x}10^{16}$ Wcm^{-2} ⇒ $\delta\lambda$= 13 nm ⇒ $\Delta t \approx 20$ fs

Intensity on target = $4\text{x}10^{17}$ Wcm^{-2} ⇒ $\delta\lambda$= 20 nm ⇒ $\Delta t \approx 13$ fs

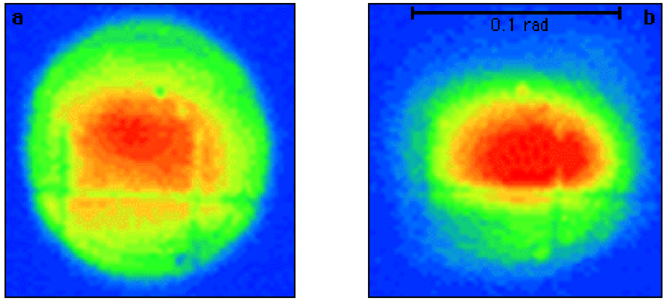
Next: Overdense propagation

OVERDENSE PROPAGATION (30 fs)

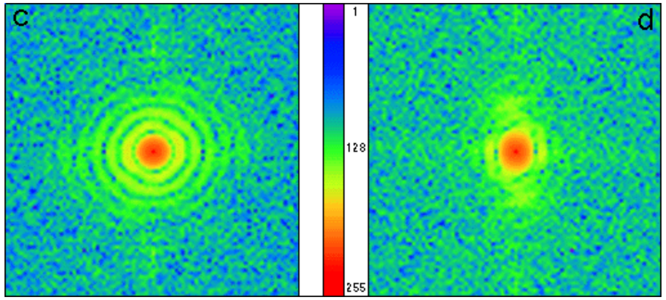
Blue-shift takes place in the presence of overdense propagation*

Near field images

No target | **0.1 μm target**

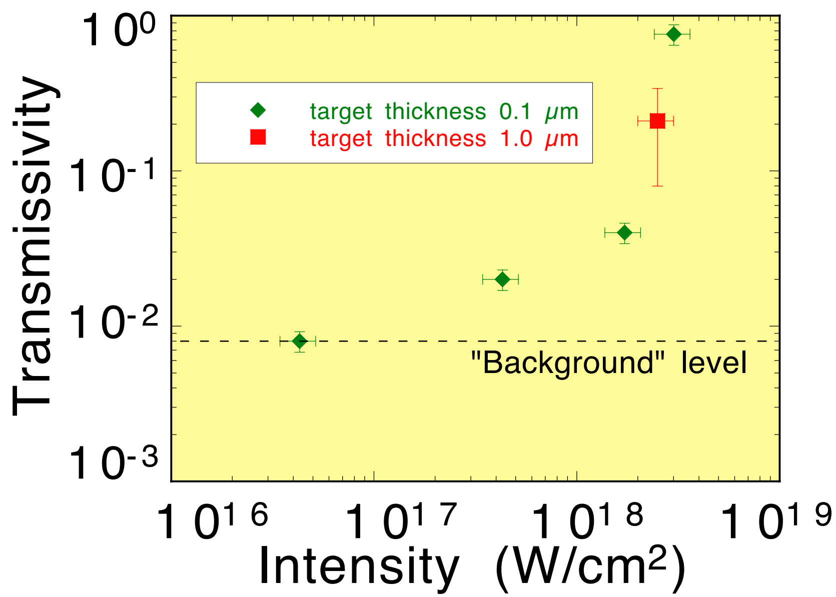


FFT of near field images



Transmission vs. laser intensity on target

30 fs laser pulse no preformed plasma



*See D.Giulietti et al.,Phys. Rev. Lett **79,** 3194 (1997)

MODELLING OVERDENSE PROPAGATION

Proposed model*: magnetically induced optical transparency of overdense plasmas due to ultra-fast ionisation

MODEL OUTLINE

- Laser light propagates through an overdense magnetised plasma as an *extraordinary* mode;
- Propagation is allowed for densities $n_e < n_c (1+\Omega/\omega)$, *where* $\Omega = eB_s/mc$ is the cyclotron frequency related to the field B_s;
- B_s is longitudinal and extremely high;

A SOURCE MECHANISM FOR B_S:

A possible mechanism for B_s has been proposed by Wilks, Dawson and Mori [PRL 61, 337 (1988)]. Their analytical and numerical simulations show that, *provided the laser field is already inside the medium*, an intense static magnetic field parallel to the oscillating magnetic field is generated as a consequence of the ultra-fast ionisation produced by an intense ultra-short pulse.

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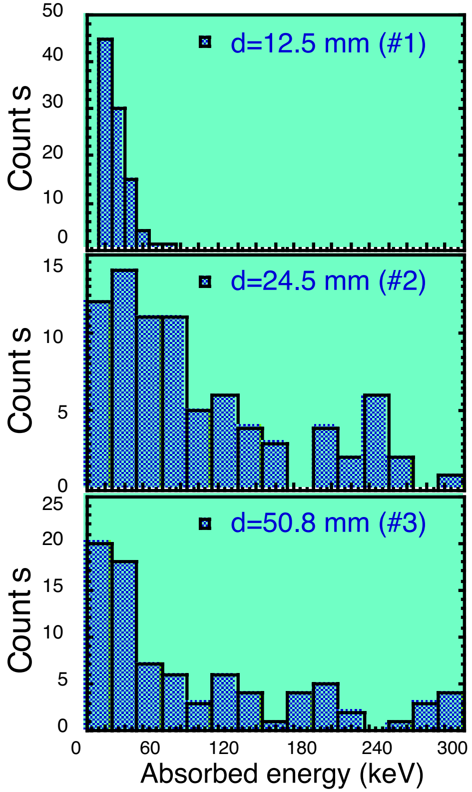
*See D. Teychenné et al., Physical Review E **58**, 1245 (1998).

GAMMA-RAY MEASUREMENTS (30 fs)

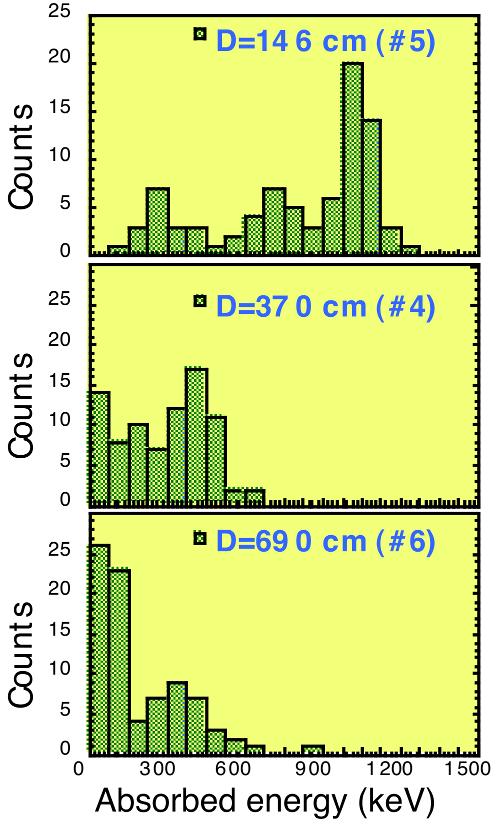
High energy photons are detected using NaI(Tl) detectors



Collimated detectors in a *near-single photon detection regime* show that photons originating directly from the target have a typical energy around 100keV.

GAMMA-RAY MEASUREMENTS (30 fs)

High energy photons arise from bremsstrahlung of hot electrons



Uncollimated detectors show that there is a large scattered photon background around 350-400 keV.
These photons are generated by the interaction of fast electrons with the target chamber (bremsstrahlung).

LOW ASE @30fs - MAIN RESULTS

- No premature plasma formation occurs.
- Blue shift of transmitted radiation provides evidence that volume ionisation is achieved.
- High transmissivity occurs at intensities above 10^{17} W/cm^2, with almost complete transparency at $3x10^{18}$ W/cm^2.
- Spatial filtering of the transmitted pulse takes place in the high transmission regime.
- High energy electrons are generated with no evidence of a peaked angular distribution.
- No second of 3/2 harmonic emission is detected

Next step: Same pulselength and HIGHER INTENSITY

PREFORMED PLASMA INTERACTIONS

For *ASE* intensities on target above 10^{12} W/cm^2 premature plasma formation occurs in laser interaction with thin foils*.

A typical exploding-foil-like density profile is generated. The peak plasma density can be varied changing the thickness of the target.

In the case of 1μm thick target and 10^{12}W/cm^2 ASE, the peak density is close to the critical density. Due to non-linear suppression of collisional absorption, the CPA pulse can propagate upward in the density gradient going through the $n_c/4$ layer up to the n_c layer.

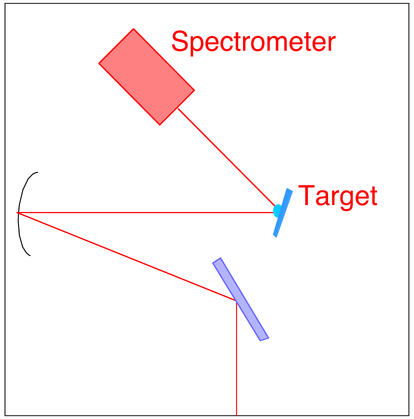
Signature of this propagation are three-half harmonic emission from $n_c/4$ and second harmonic emission from n_c.

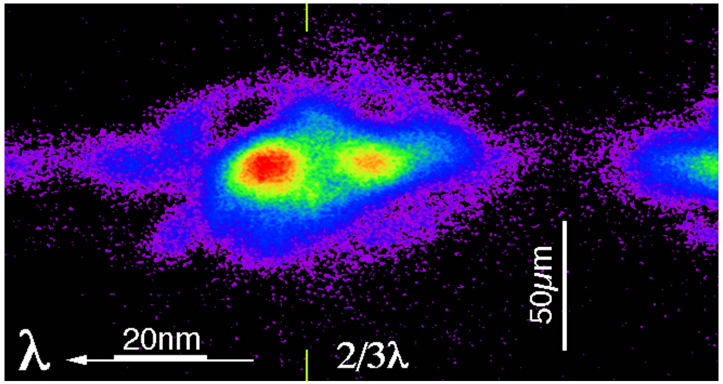
* See: A.Giulietti et al.,Phys. Rev. Lett **63,** 524 (1989)

CPA INTERACTION WITH PREFORMED PLASMAS-1

Two plasmon decay takes place in the precursor plasma at $n \approx n_c/4$. Spectroscopic evidence of TPD is given by 3/2 ω_L emission

Space resolved spectra of specular 3/2 ω_L are very broad and spatially localised on the main peak of the laser spot on target. Both red and blue components are present.





Target tickness: 1 μm

ASE intensity ≈ 10^{12} W/cm²

ASE duration ≈ 10ns

CPA intensity ≈ 10^{19} W/cm²

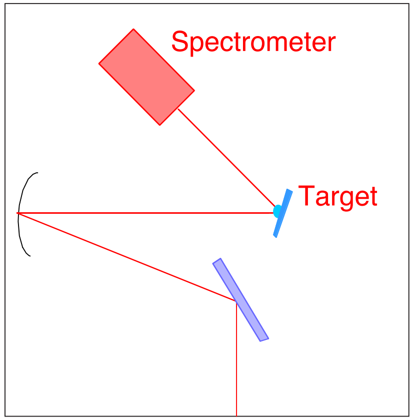
CPA duration ≈ 35 fs

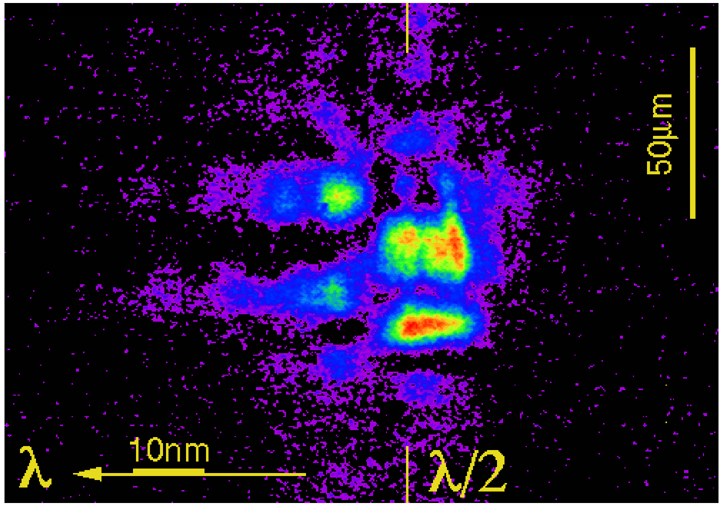
✓ No 3/2 ω_L emission was detected in the absence of a precursor plasma

CPA INTERACTION WITH PREFORMED PLASMAS-2

Specular second harmonic emission is a clear signature of interaction of the CPA pulse with the critical density plasma

Space resolved specular 2 ω_L spectra show complementary blue and red shifted regions. Blue-shift originates from regions where additional ionisation takes place.





Target thickness: 1 μm

ASE intensity≈ 10^{12} W/cm^2

ASE duration≈10ns

CPA intensity≈5x10^{18} W/cm^2

CPA duration≈35 fs

MATCHING LASER WAKEFIELD ACCELERATION CONDITIONS IN THIN FOIL INTERACTIONS

Pre-formed plasma conditions can be *tuned* to match LWA criterion for the 30 fs, 800mJ LOA laser pulse.

LWA: optimum electron density for a 30 fs laser pulse is $n^*=2\text{x}10^{18}$ cm^{-3}

We use the ASE to explode the target and produce the required plasma:

- **2D hydrodynamic simulations show that with the *measured ASE* of 10^{14} W/cm^2, a long scale-length plasma with a peak density of $2\text{x}10^{18}$ cm^{-3} can be achieved with a ≤1μm thick target.**
- **The main CPA pulse propagates in a plasma with a longitudinal scale-length of ≈200 μm with an intensity of 10^{20} W/cm^2.**
- **Hydrodynamic simulations also predict the presence of a weak density depression (channel) on the propagation axis**

HOW IS THE INTERACTION INVESTIGATED

We use X-ray, γ-ray and optical diagnostics to determine the kind of interaction regime achieved in our experiments

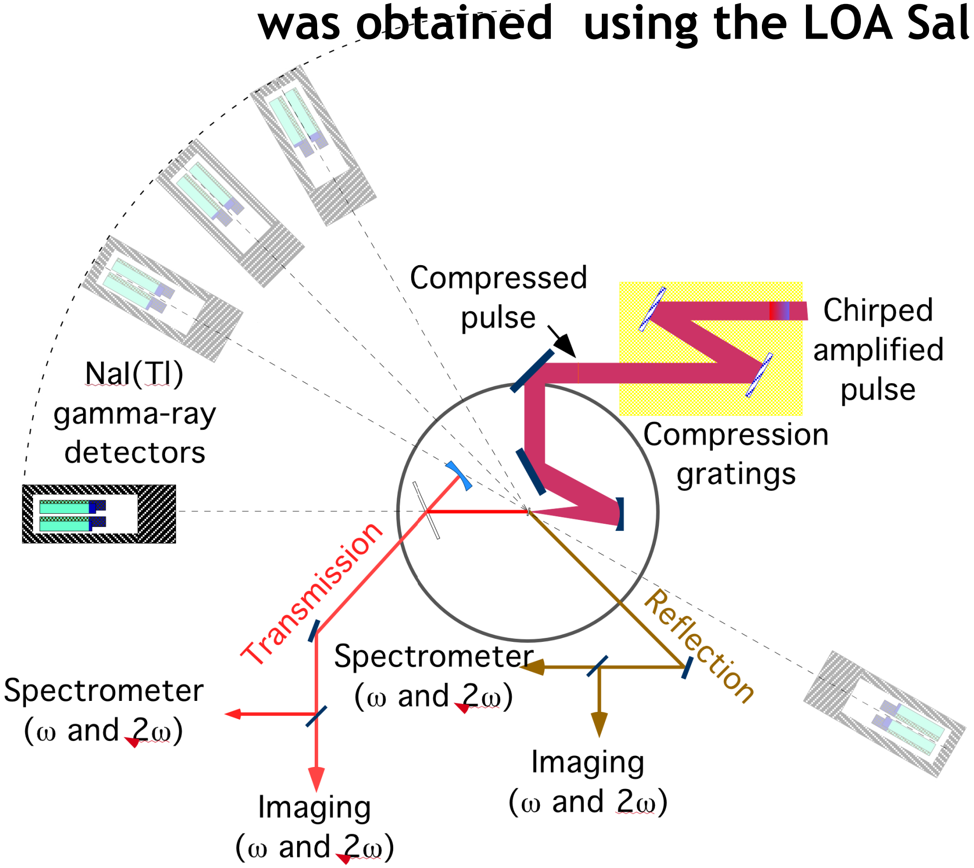
- **The properties of accelerated electrons are measured by detecting γ -ray (>100keV) emission intensity, spectral and angular properties.**

- **Optical measurements of transmitted and reflected radiation at the fundamental and second harmonic frequency tell us about the degree of coupling between the laser and the plasma.**

- **Hard X-ray measurements (<100keV) enable a fast tuning of focusing conditions and a discrimination between primary processes (arising directly from the target) and secondary processes (arising from interaction of LW accelerated electrons)**

ULTRAINTENSE CPA INTERACTIONS

CPA interaction at 10^{20} W/cm^2 with underdense preformed plasma was obtained using the LOA Salle Jaune laser.



Target tickness: 0.1 and 1.0 μm

ASE intensity≈ 2x10^{13} W/cm^2

ASE duration≈10ns

Max CPA intensity≈10^{20} W/cm^2

CPA duration=30 fs

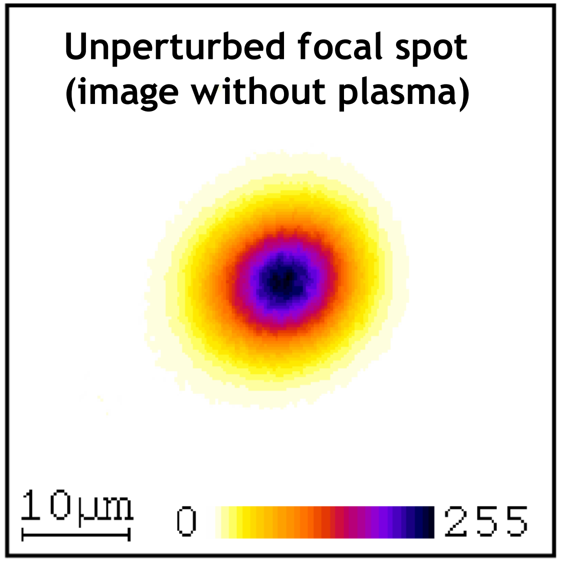
Laser wavelength=825 nm

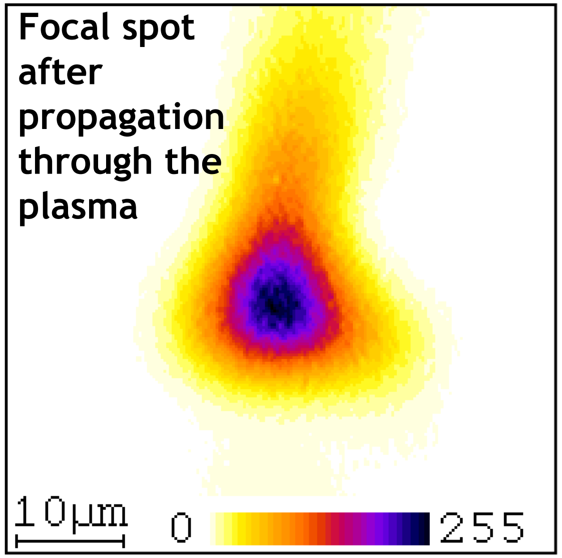
CPA energy on target≈800 mJ

CPA/ASE (contrast ratio)≈2x10^6

OPTICAL MEASUREMENTS - 1

Images of the focused CPA laser pulse are taken just after the interaction region and are compared with the unperturbed focal spot

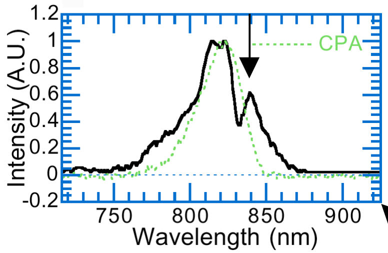


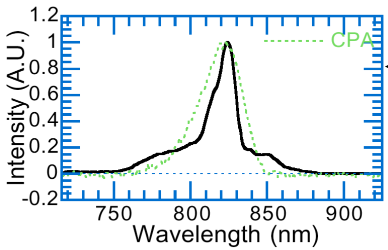


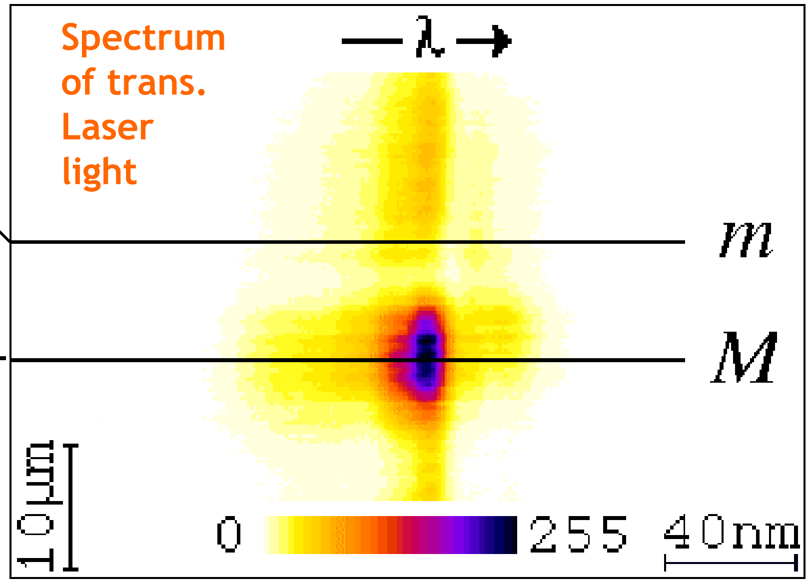
- Laser pulse intensity distribution after the plasma is only marginally affected by propagation through the long-scale-length plasma.
- A small fraction of the incident light is reflected or scattered at large angles

OPTICAL MEASUREMENTS - 2

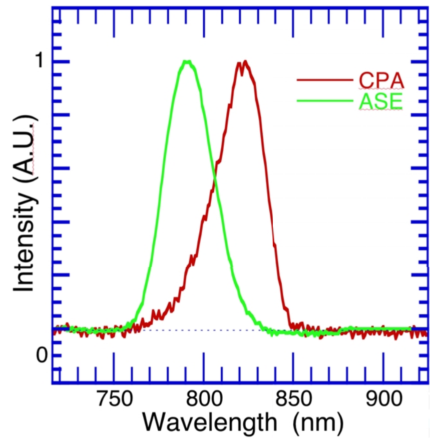
Spectra of transmitted laser radiation are resolved in space







ASE is blue-shifted with respect to CPA

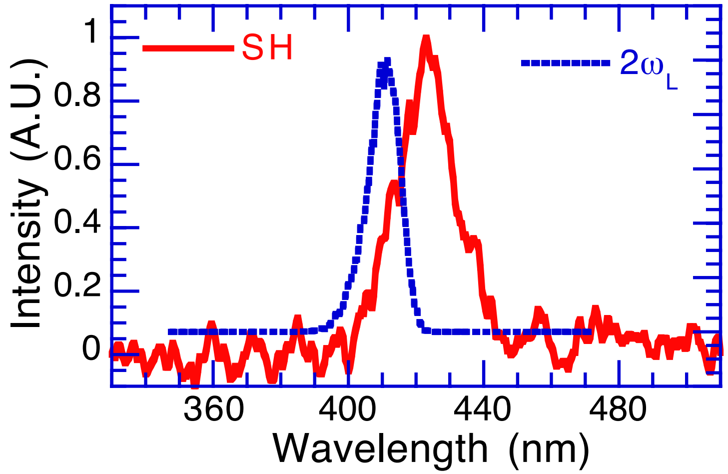


- The main portion of the pulse (on axis) exhibits a clear spectral narrowing
- The blue tail of the spectrum is due to a residual contribution of ASE.
- The off-centre red-shifted peak can be explained in terms of SPM due to density rarefaction.

OPTICAL MEASUREMENTS - 3

Second harmonic emission is only observed in marginal positions and shows a substantial red-shift

- Imaging of forward second harmonic emission shows that SH sources are located at marginal positions.
- Spectra of such a SH emission show a clear red shift, exactly twice the frequency of the off-centred red-shifted peak observed at the fundamental frequency.



✓ SH emission is correlated to laser-plasma coupling processes outside the main interaction region where larger density plasma non-uniformities exist.

OPTICAL MEASUREMENTS - summary

Optical measurements show two distinct interaction regions

• The inner part of the laser beam propagates in a long-scale-length plasma without significant perturbation or disruption of the intensity pattern.

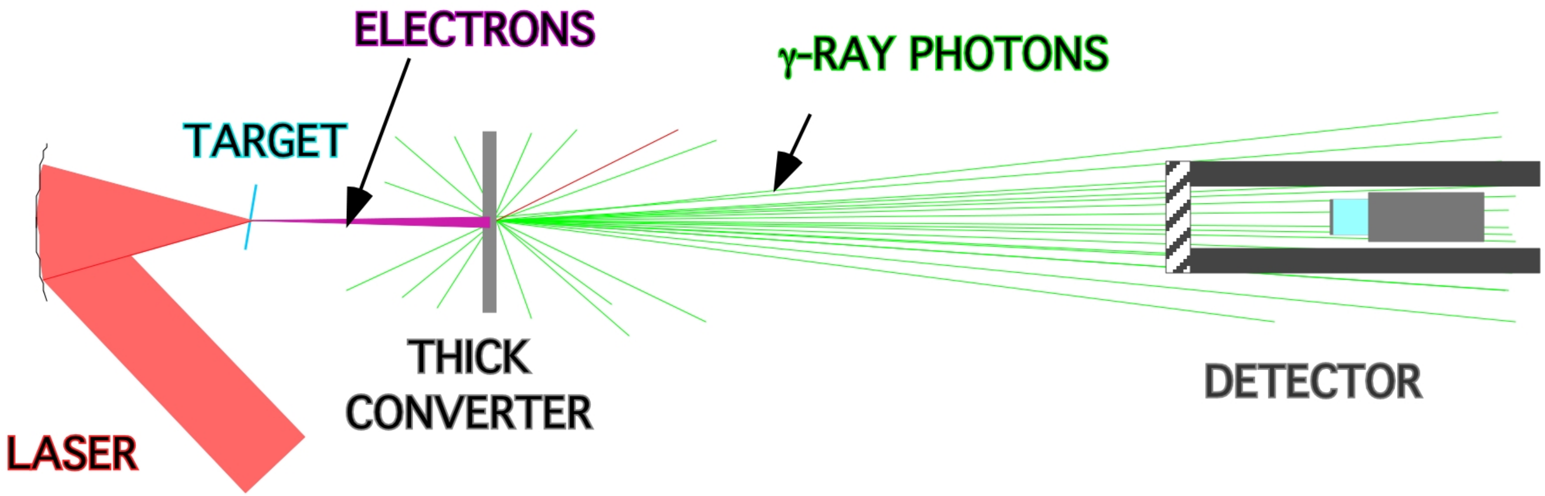
• A very small fraction of the laser energy is scattered or reflected at large angles and interacts with colder, inhomogeneous plasma regions undergoing SPM, second harmonic conversion etc.

• These measurements suggest that suitable conditions for high-energy electron acceleration my take place in the propagation region: the CPA pulse propagates with an intensity of 10^{20} W/cm^2 in a plasma of peak density of 2×10^{18} cm^{-3} with a longitudinal scale-length of $\approx$200 μm.

• We look at electron acceleration processes by detecting bremsstrahlung radiation arising from the interaction of such fast electrons with matter.

BREMSSTRAHLUNG TECHNIQUE -1

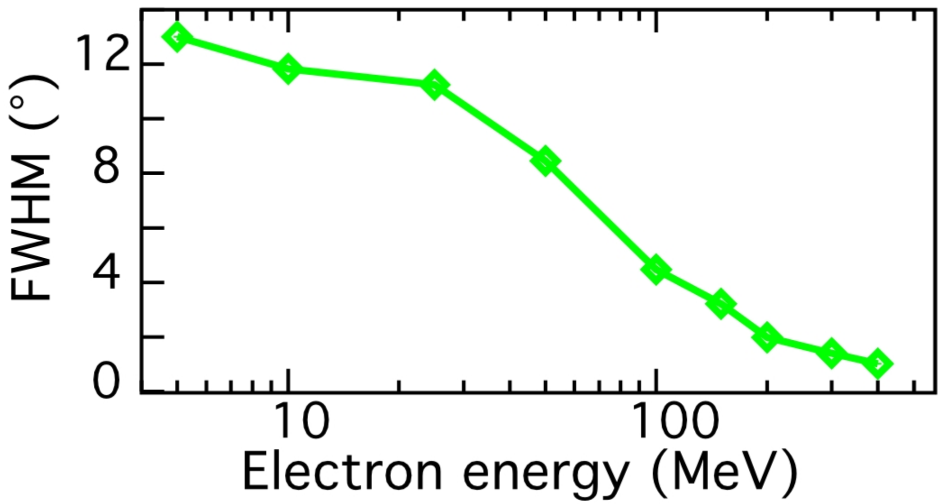
Spectral and angular properties of fast electrons generated during the laser-plasma interactions are retrieved studying bremsstrahlung γ-ray photons.



- Bremsstrahlung of high energy electrons (>MeV) is confined in a cone of aperture ($\alpha \sim 1/\gamma$). This ensures that the electron angular distribution is preserved.
- The spectral properties of incident electrons can be obtained by comparison of measured signals with predictions of Montecarlo simulations (GEANT)

BREMSSTRAHLUNG TECHNIQUE -2

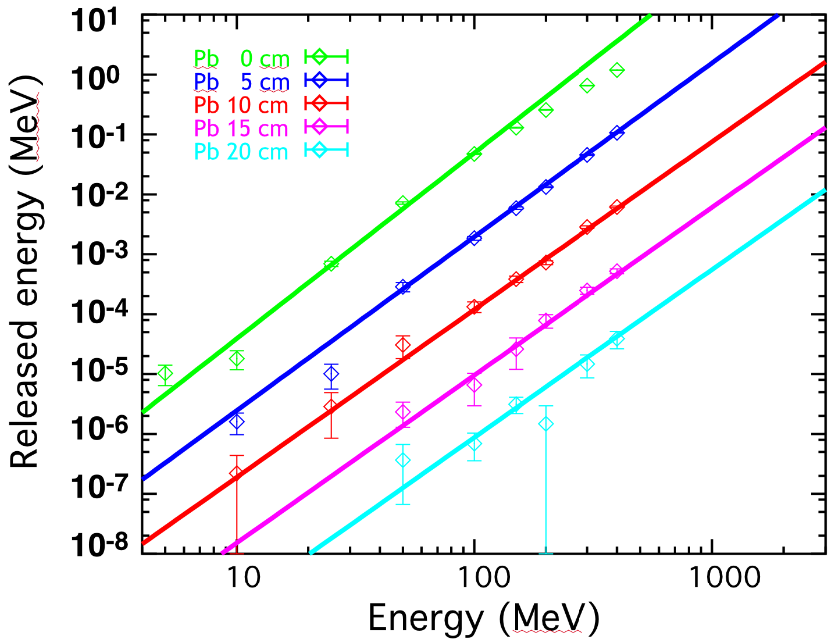
Angular spread of bremsstrahlung photons is small for relativistic electrons



- Montecarlo (GEANT) simulations for our exact experimental set-up enables us to take into account the angular spread due to bremsstrahlung conversion.
- **The technique works best for very large electron energies where traditional electron spectrometers based upon magnetic field become heavy and bulky.**

BREMSSTRAHLUNG TECHNIQUE -3

Lead blocks attenuate/filter γ-rays reaching the detectors.



According to Montecarlo simulations (GEANT) the energy released by γ-rays in the NaI scintillators after propagation in lead

1) Increases with the photon energy (power law)

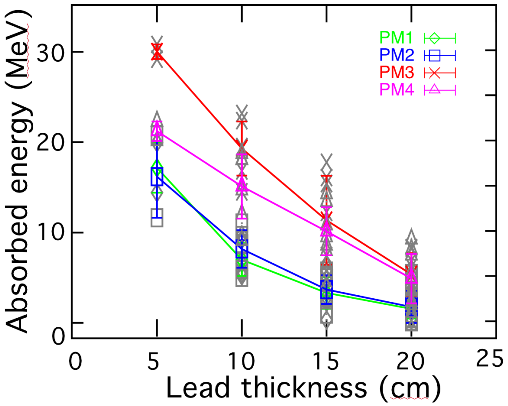
2) decreases by one order of magnitude every 5cm of lead (exponential law) for all energies

- Small layers of led (<< 5cm) can be used for energy discrimination purposes.
- After the first 5cm, lead acts as a simple, energy independent attenuator

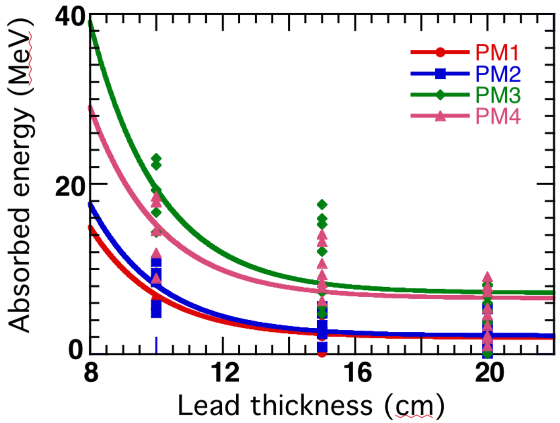
DIFFUSED γ-RAY BACKGROUND

Signal consists of two components: a collimated one originating from primary electrons and diffused one due to secondary scattering.

Raw data show a weak dependence on lead thickness.



The diffused component is obtained fitting the data with $S(x) = S_c A^{-x/x_0} + B$



S_c collimated c.

A att@5cm Pb

x_o Pb thickness

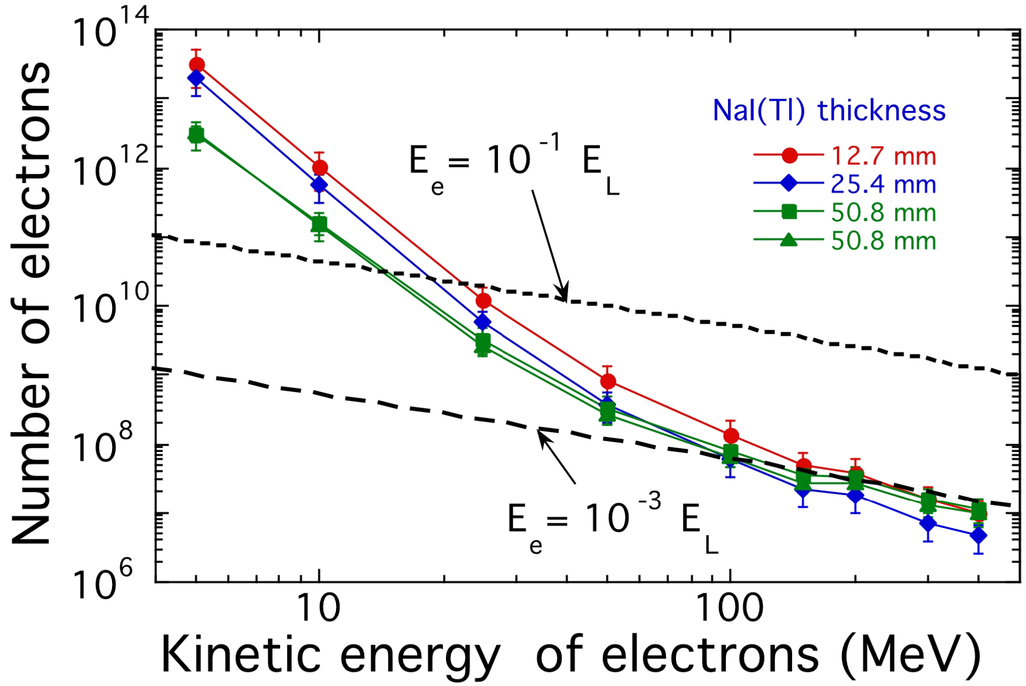
B diffused c.

- **Fitting suggests that signal after 15 cm Pb is mostly due to diffused component**
- **Diffused component can be further reduced increasing the collimation efficiency**

ELECTRON ENERGY MEASUREMENTS

Total input laser energy sets the lower limit on fast electron energy

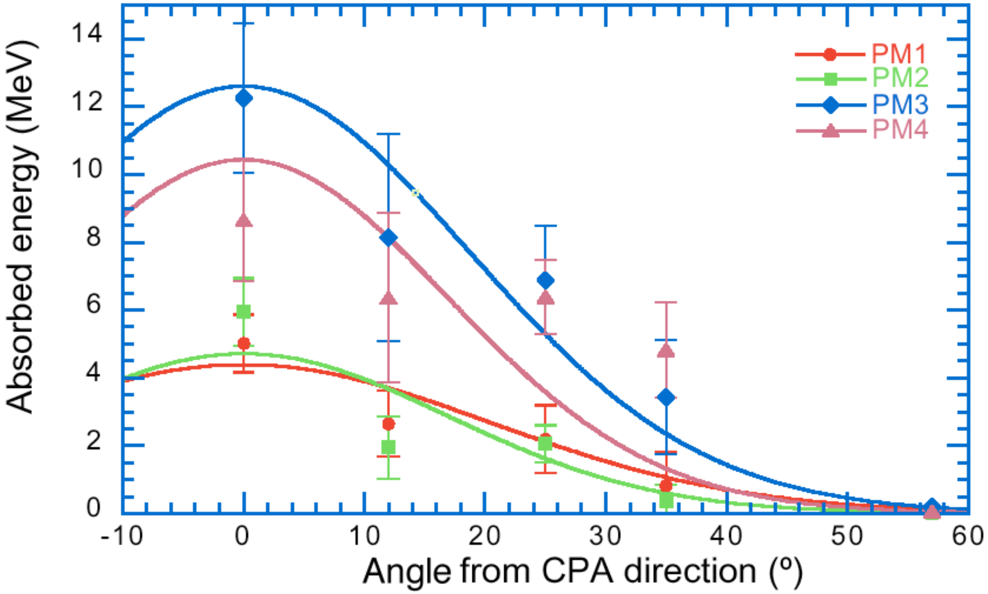
Montecarlo simulations of our exact experimental conditions compared with esperimental results identify possible *electron number vs.electron energy* curves



Assuming a conversion efficiency into fast electrons of 10^{-3}, Montecarlo simulations require a minimum energy of 100 MeV to explain observed γ-ray signals.

ANGULAR DISTRIBUTION OF γ-RAYS

Angular distribution of γ-rays is peaked along the CPA direction.



Fitting curve:

$$S_c = A\exp\left(8\ln 2\frac{\cos\theta}{\theta_{FWHM}^2}\right)$$

θ_{FWHM}= 42.5 ± 0.5°

Further analysis is in progress to take into account electron energy distribution and angular broadening due to bremsstrahlung.

CONCLUSIONS

- Dramatically different laser-plasma interaction regimes take place in ultra-intense laser-solid interactions depending on the laser pulse features on the ns and ps time-scale.

- Thin plastic foils have been successfully used to perform interaction experiments with ultra-short, ultra-intense CPA laser pulses under controllable conditions.

- Strong, polarisation dependent laser-plasma coupling in steep density gradients has been studied at intensities up to 5×10^{17} W/cm^2.

- Laser-solid interactions with consequent ultra-fast ionisation of matter has been achieved at intensities up to 3×10^{18} W/cm^2

- Finally, it was shown that thin foils can provide suitable conditions for the acceleration of electrons in ASE-dominated, single beam CPA interactions up to 10^{20} W/cm^2.

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