Frequency-domain interferometry diagnostic system for the detection of relativistic plasma waves

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Introduction

Relativistic Plasma Waves Can Accelerate Electrons

• Relativistic Plasma Waves have phase velocities, $v_{phase} \cong c$

• Externally injected electrons can "surf" these waves and get accelerated with gradients of few GeV/m (100 – 1000 times more than conventional accelerators)

• Plasma accelerators could be << in size than conventional accelerators (and therefore much cheaper)

• Relativistic Plasma Waves can be excited by the beat pattern of an intense, two-wavelength laser pulse

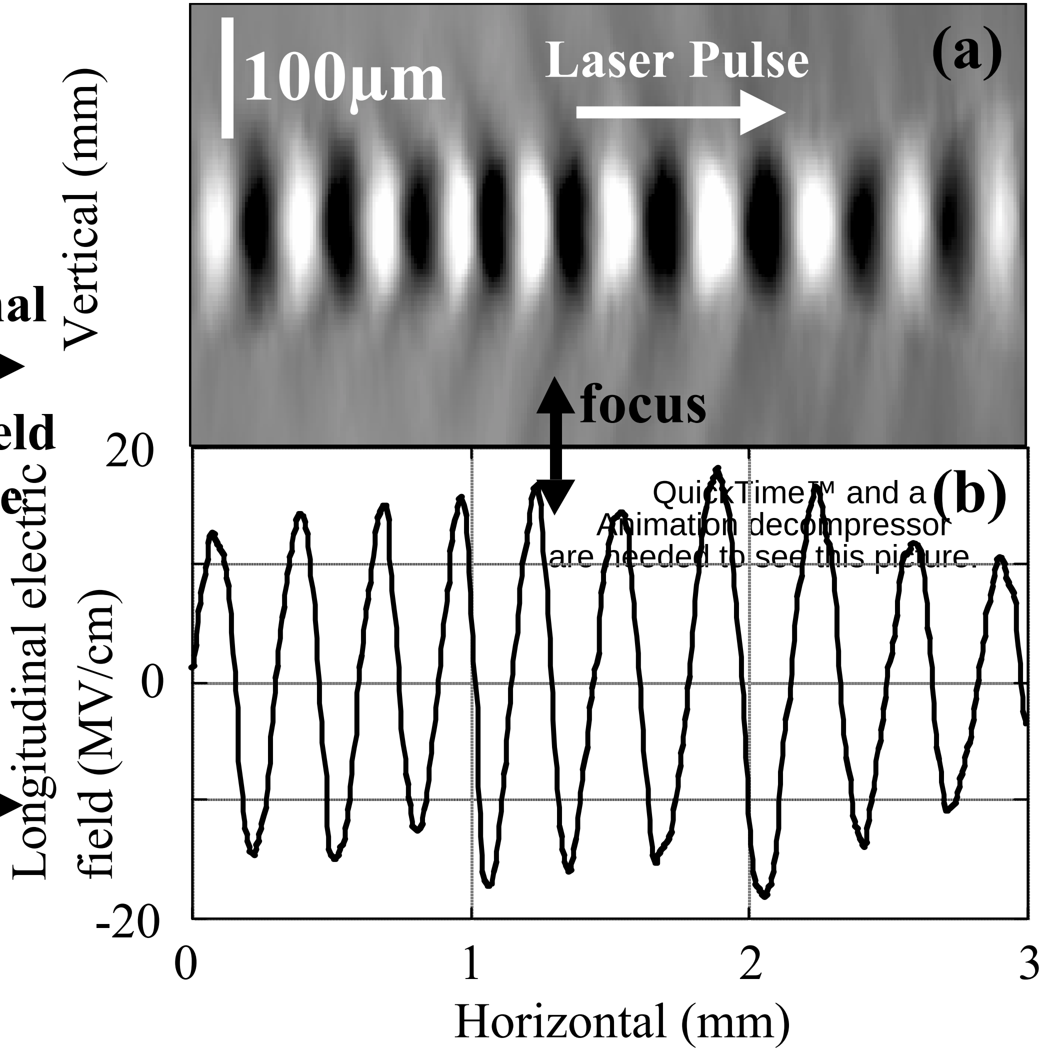
Introduction

Relativistic Plasma Waves Can Accelerate Electrons

Longitudinal

Electric Field Of the wave

Laser

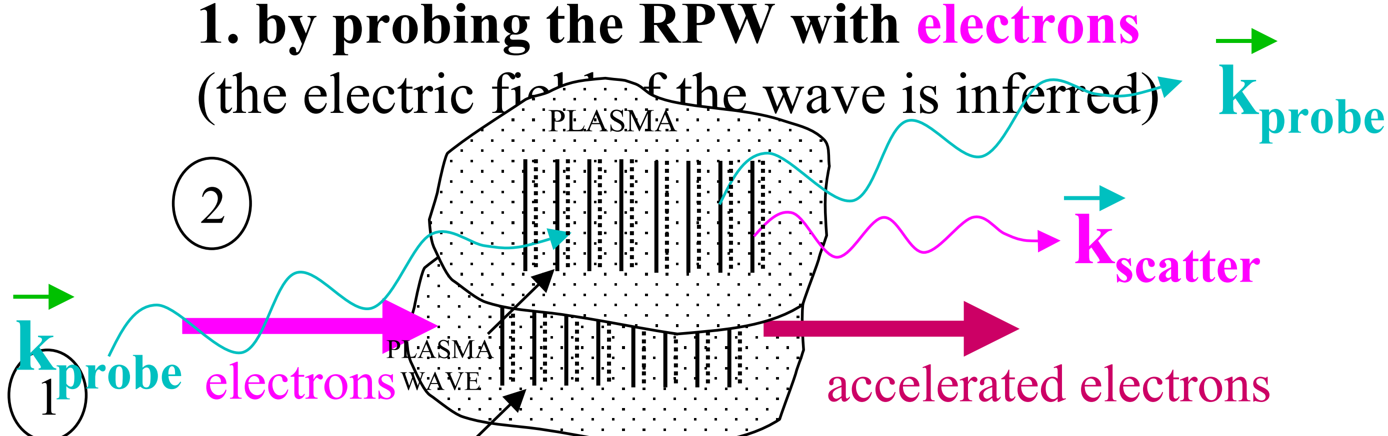


Relativistic Plasma Waves (RPWs) Detection Techniques

There are TWO major ways to detect a RPW

2. by probing the RPW with light (photons)
(the absolute density perturbation δn is inferred)

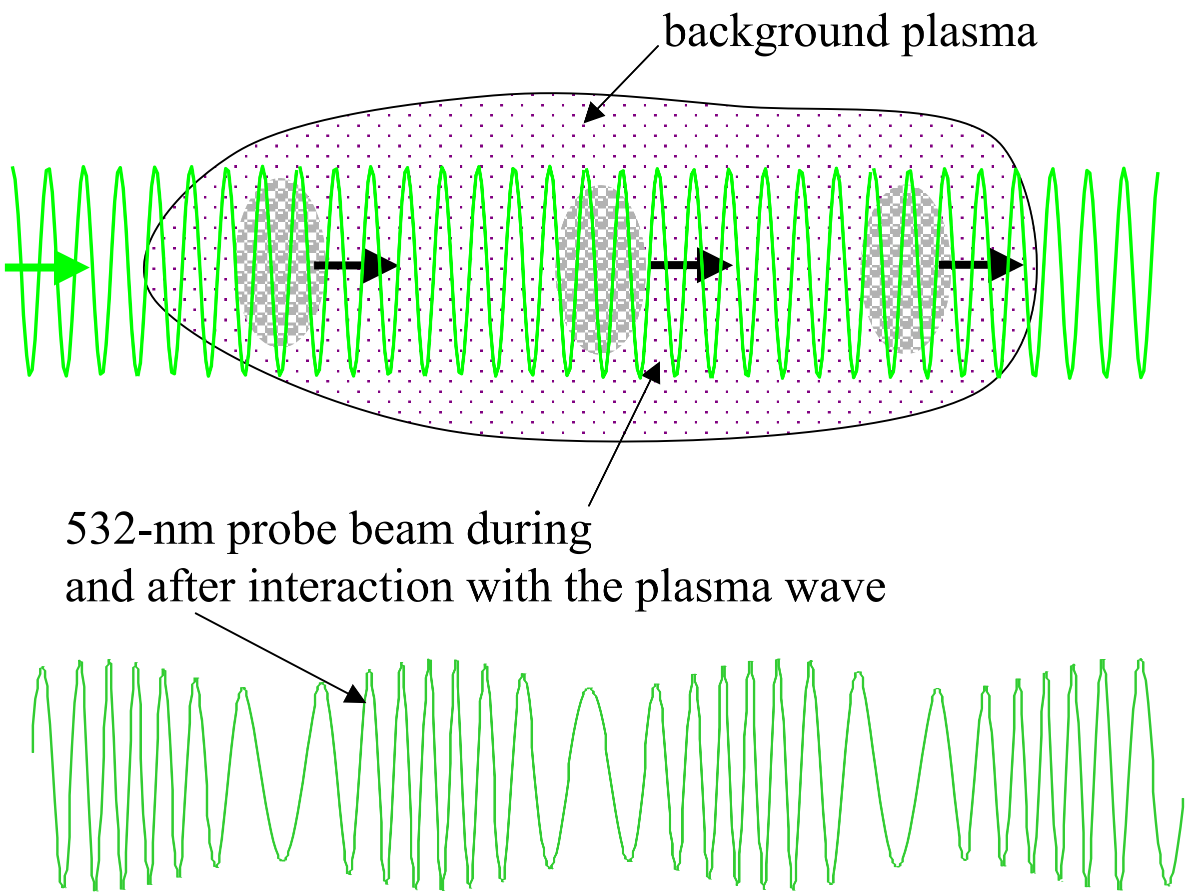
1. by probing the RPW with electrons
(the electric field of the wave is inferred)



$$\omega_{scatter} = \omega_{probe} \pm \omega_{epw}$$

$$\vec{k}_{scatter} = \vec{k}_{probe} \pm \vec{k}_{epw}$$

Detection of Relativistic Plasma Waves- Collinear Thomson Scattering



probe beam gets modulated in phase (and amplitude)

η = index of refraction in a plasma:

$$\eta = \sqrt{1 - \frac{n}{n_{crit}}} < 1$$

For a 532-nm light wave going through a plasma a change in plasma density of

$\delta n = 10^{14}\ \mathrm{cm}^{-3}$

(1% wave at $10^{16}\ \mathrm{cm}^{-3}$)

is equivalent to a change in the index of refraction of

$\delta\eta \cong 10^{-8}$

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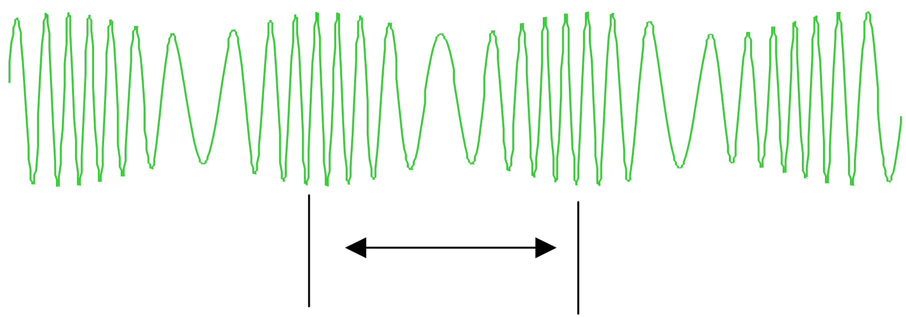
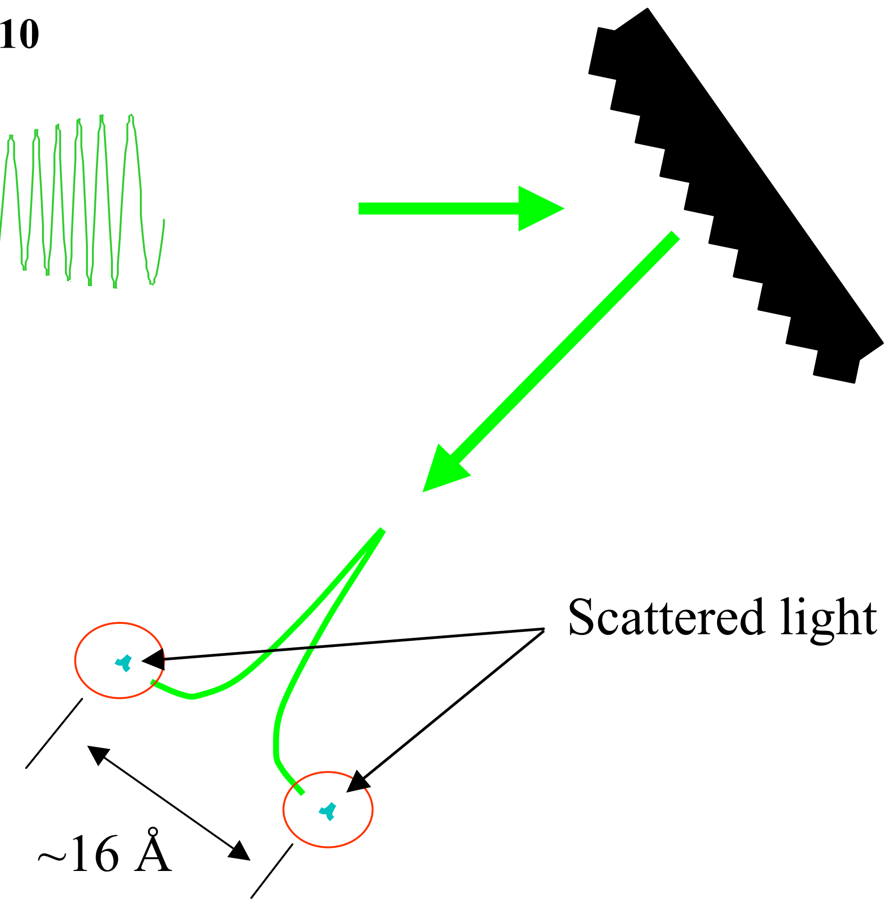
Amplitude modulation is

10^{-8} - 10^{-10}



period = 1 ps

ν = 1 THz



for a plasma density of 10^{16} cm^{-3}

$$\frac{P_s}{P_0} \sim \left[\delta n\ (\mathrm{cm}^{-3}) \times \lambda_{probe} \times L_{inter} \right]^2$$

Relativistic Plasma Waves (RPW) Detection at UCLA - Goals

1. Detection of the longitudinal component of RPW
2. Detection of RPW at low densities (10^{15} cm^{-3} to 10^{17} cm^{-3})
3. Good signal-to-noise ratio (1000 to 1)
4. Frequency and time-resolved (both red and blue shift)
5. Use of independent probe to avoid stray scattering
6. Easy to implement, reliable, on-line with electrons

Experimental challenges

1. Scattering lasts for ~***100 ps*** => **MUST** use streak camera => **MUST** use visible pulses for probing => Very small scattering efficiency

   $\mathbf{P_{scattered}/P_{probe} \cong 10^{-8} - 10^{-10}}$ => **MUST** use MW-power probe laser pulses with duration ≥ 2ns for easy synchronization => Pulse energy is high => **MUST** use high-damage threshold optics

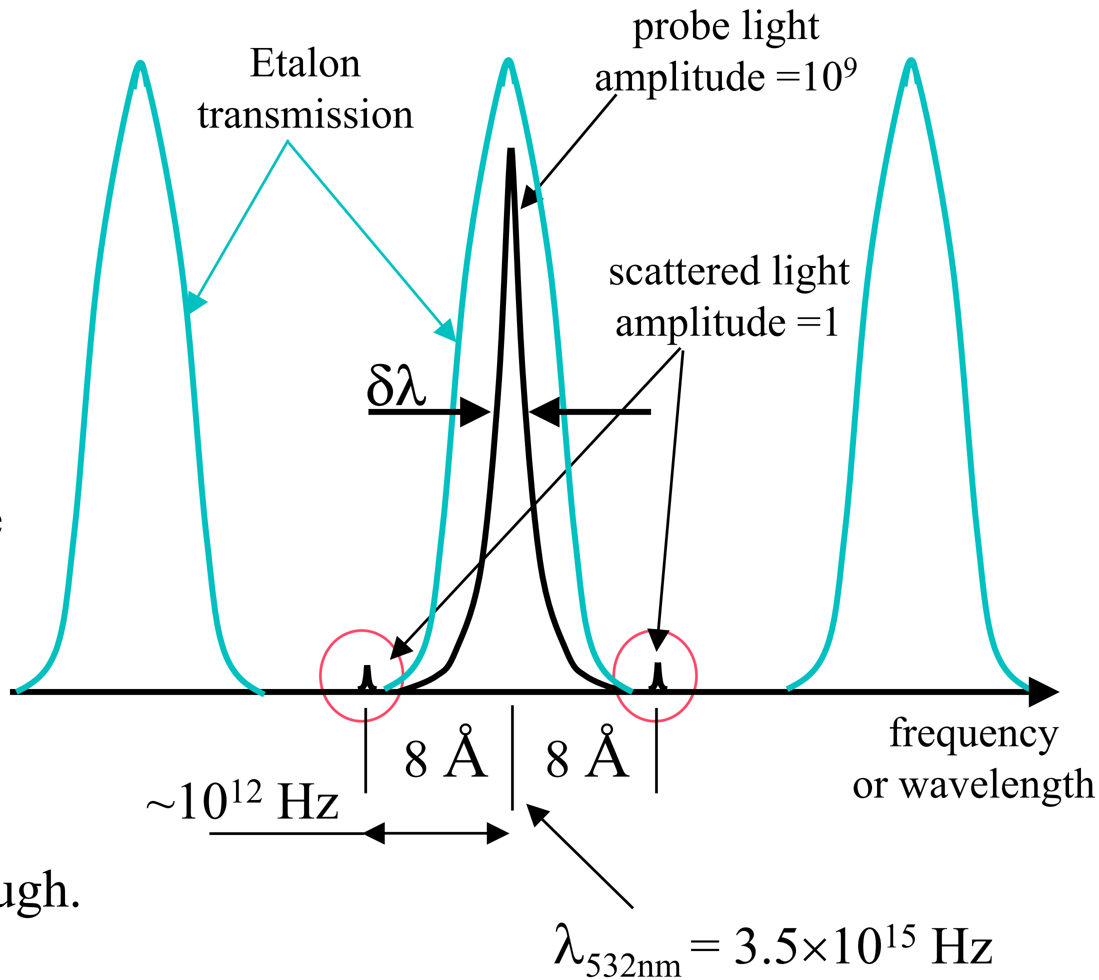
2. The **VERY WEAK** scattered light is only ~8 Å away from the **VERY INTENSE** probe light

Experimental considerations

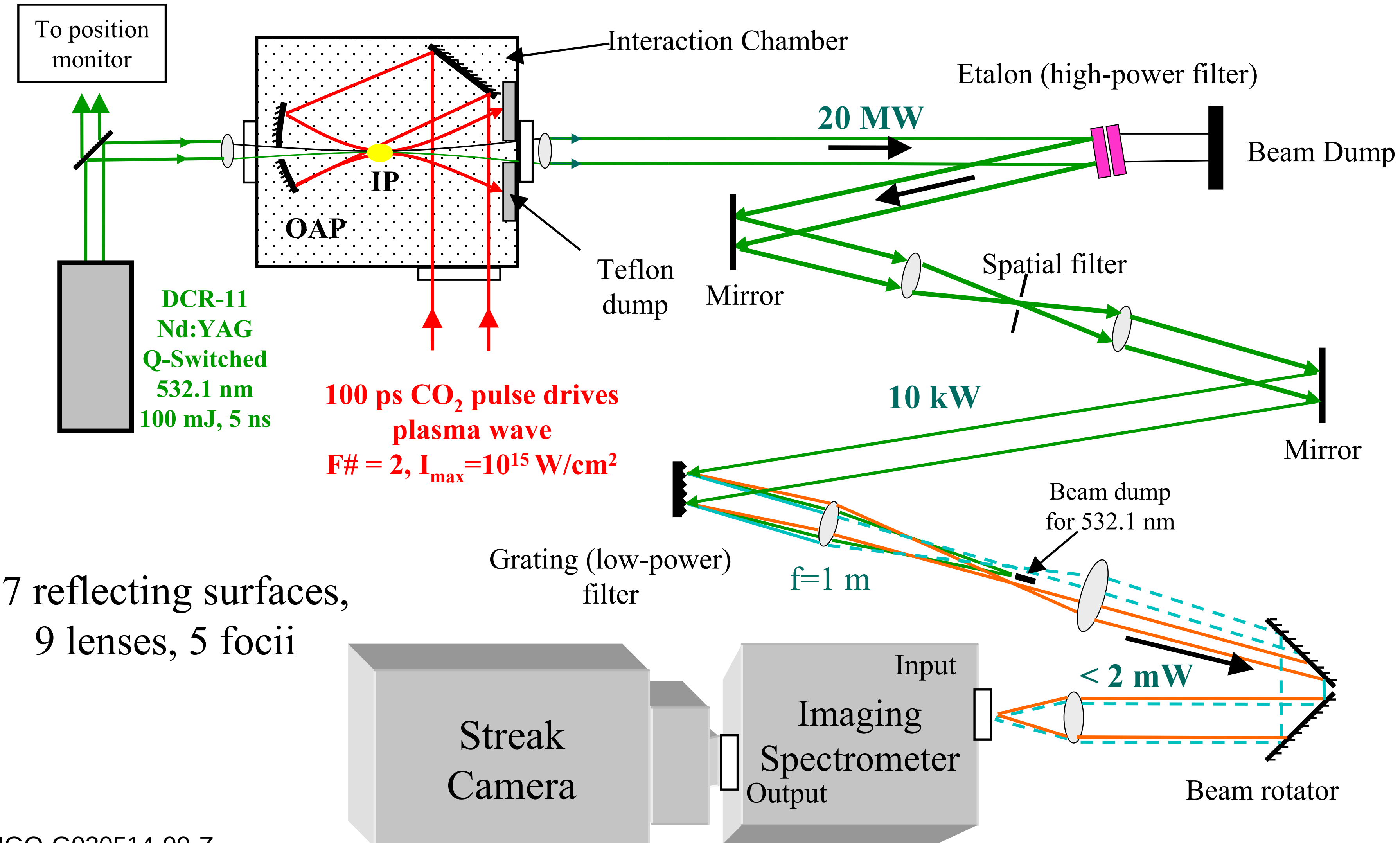
1. First use a "power" filter to decrease the power of the probe pulse (~1000 times) in order to use a grating afterwards

2. Use an etalon with high-damage threshold coatings as a "power" filter.

3. Hope that the bandwidth of the probe laser pulse is narrow enough.

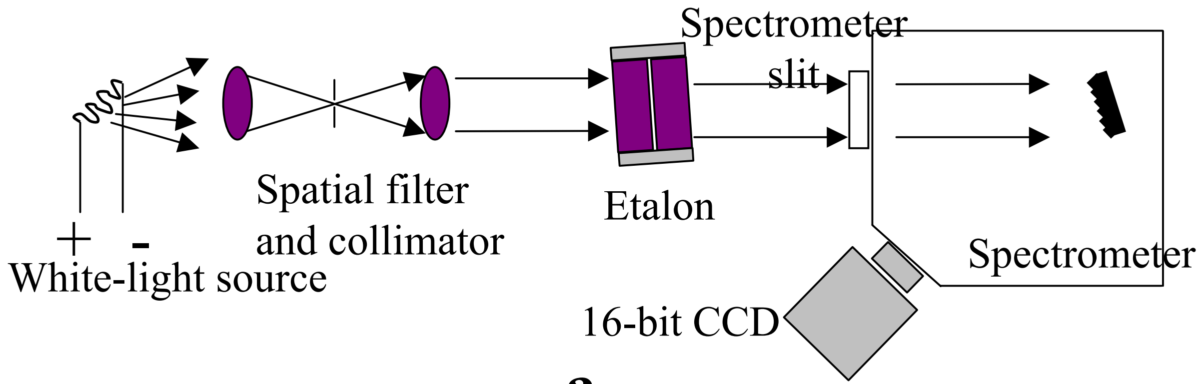


Experimental Setup For Frequency And Time Resolved Collinear Thomson Scattering

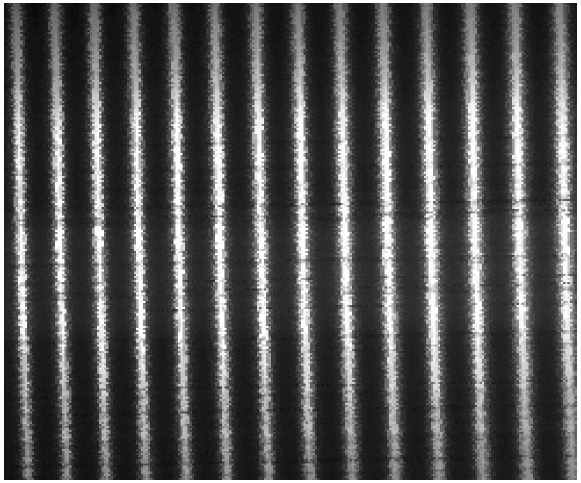


27 reflecting surfaces,
9 lenses, 5 focii

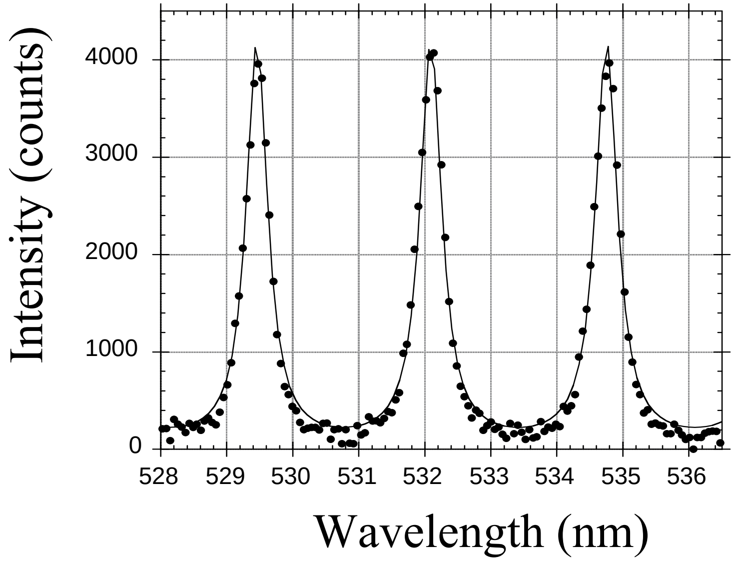
Etalon preliminary test and measurements



a



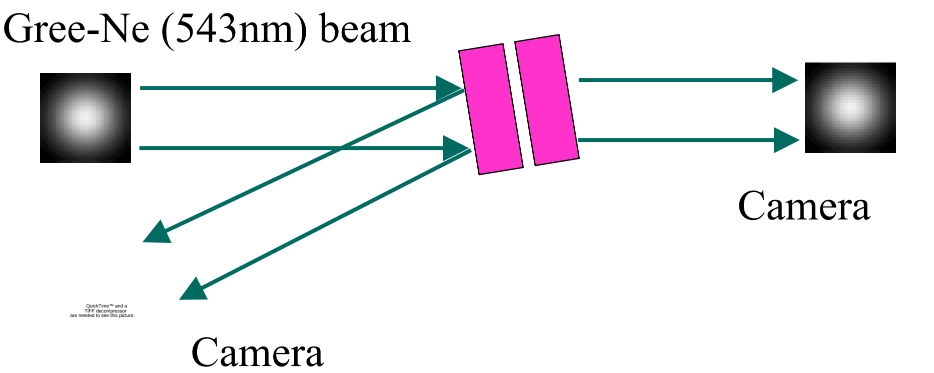
b



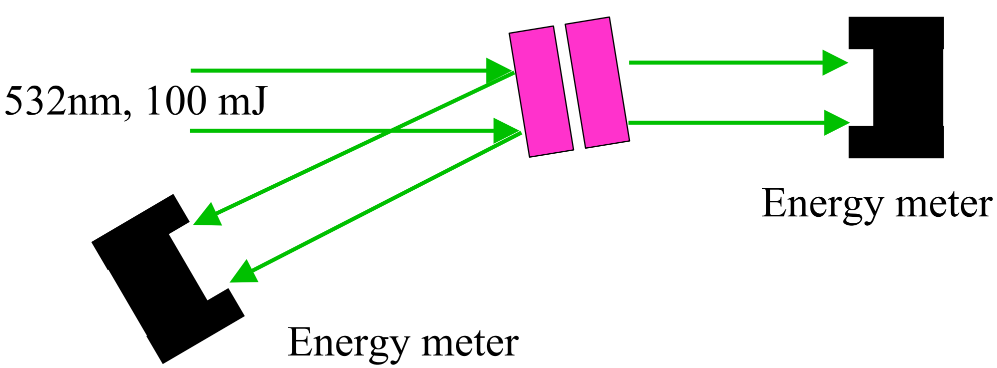
c

Etalon preliminary test and measurements

Attenuation of the probe pulse at 532.1 nm is only ~10 times!

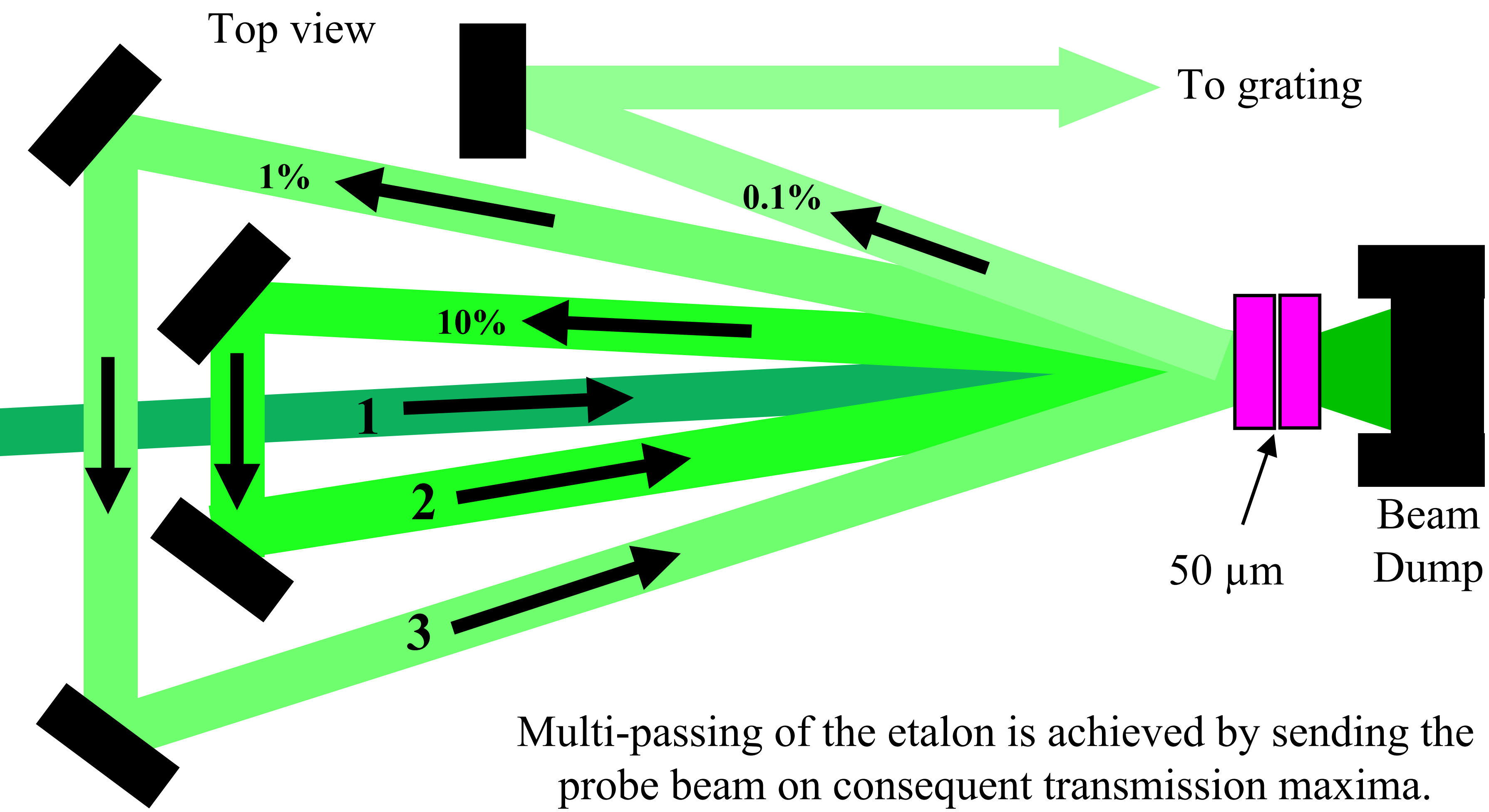


QuickTime™ and a
TIFF decompressor
are needed to see this picture.



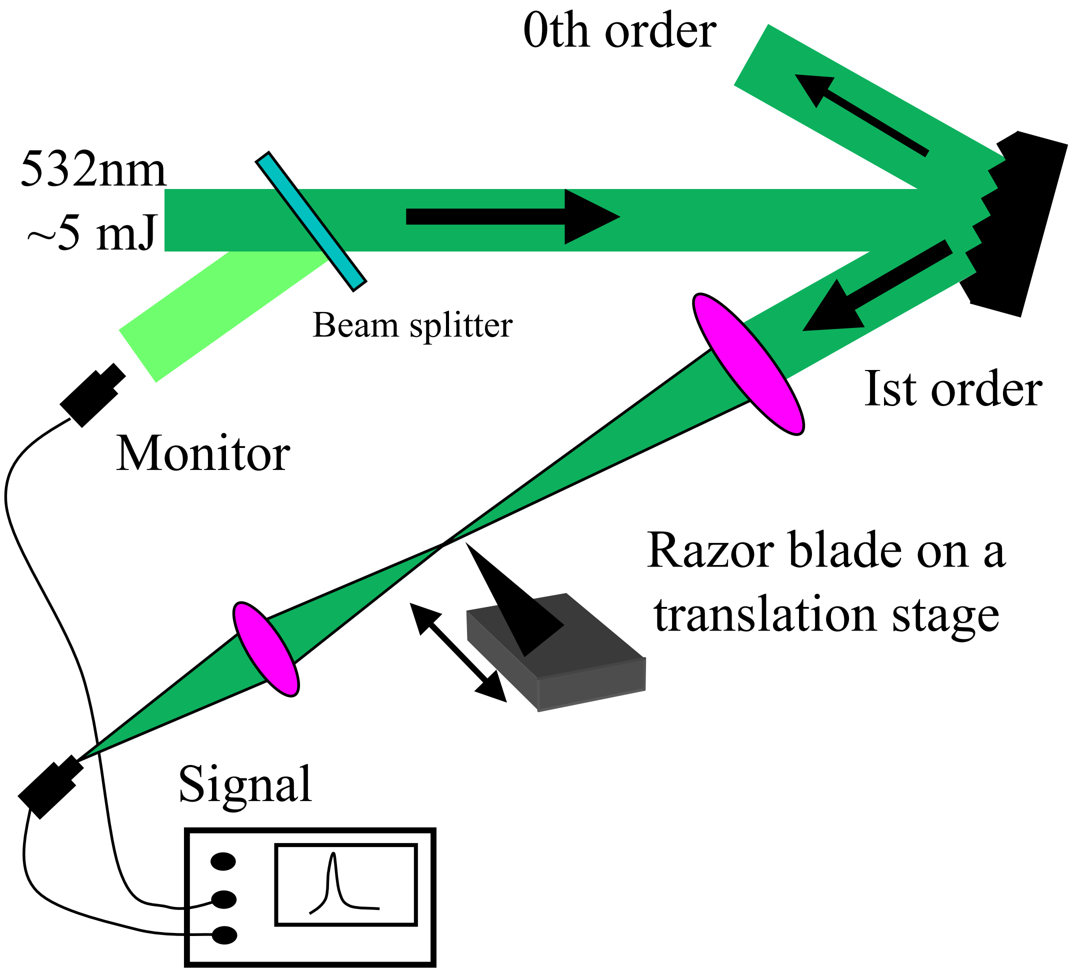
Profile of the reflection of the
543 nm Gaussian He-Ne gas laser beam

Multi-passing of the Etalon

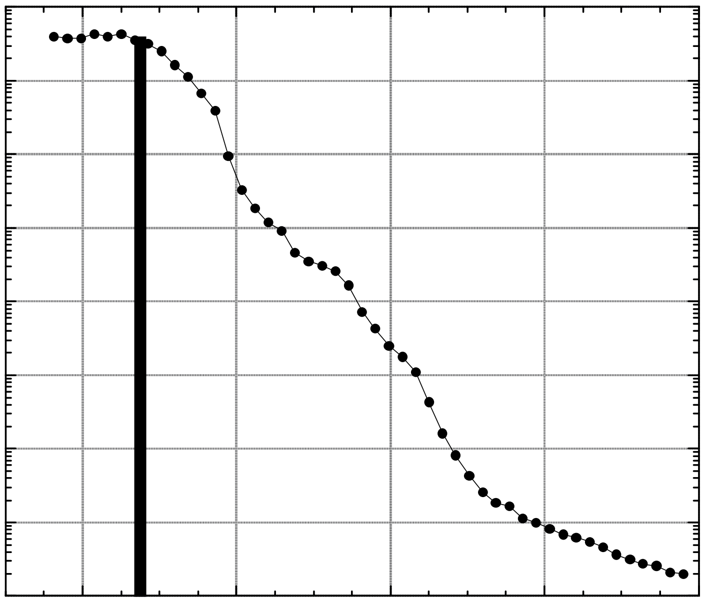


Multi-passing of the etalon is achieved by sending the probe beam on consequent transmission maxima.

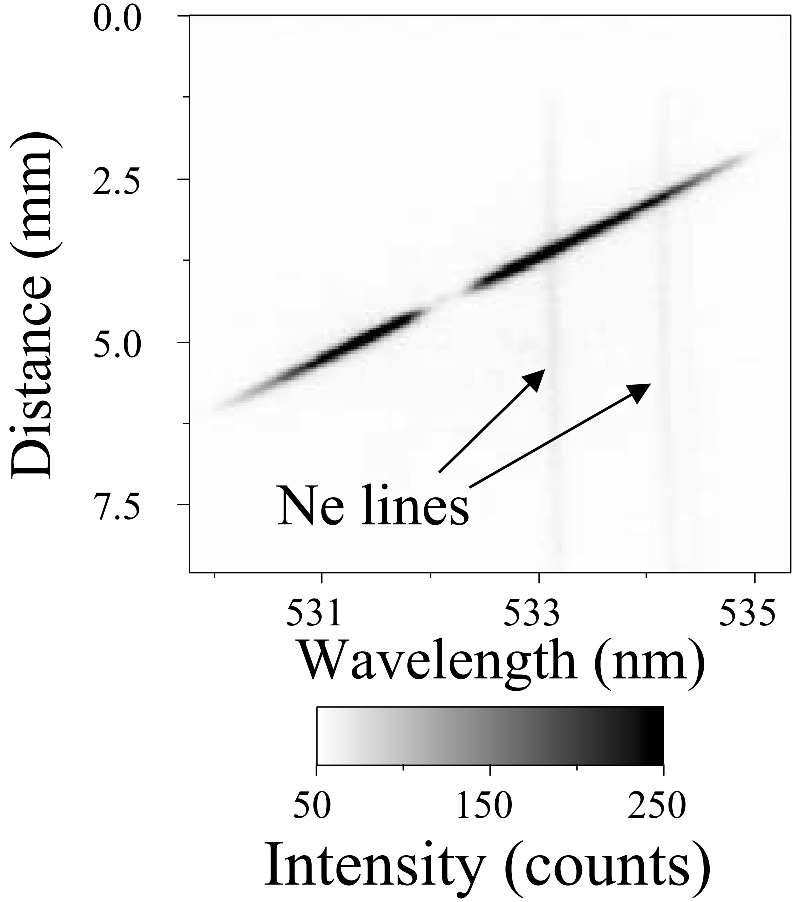
Grating preliminary test and measurements



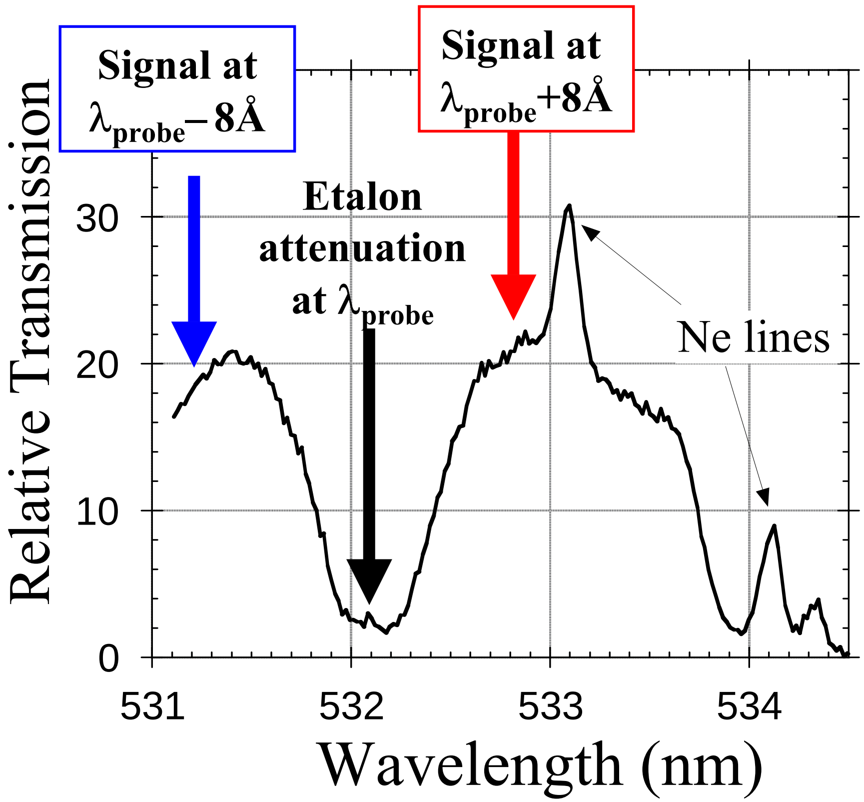
The grating can reduce the probe light ~10^7 times without attenuating the scattered light



White light measurements



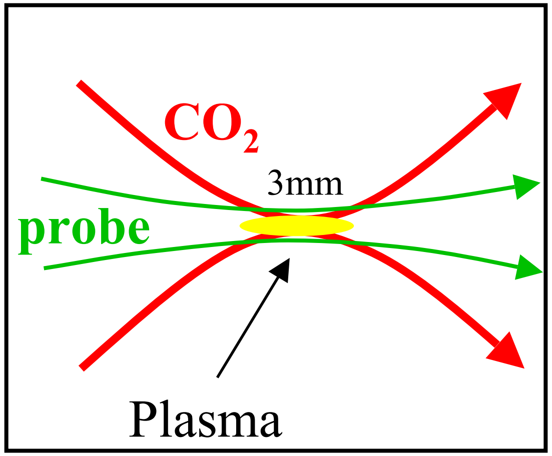
(a)

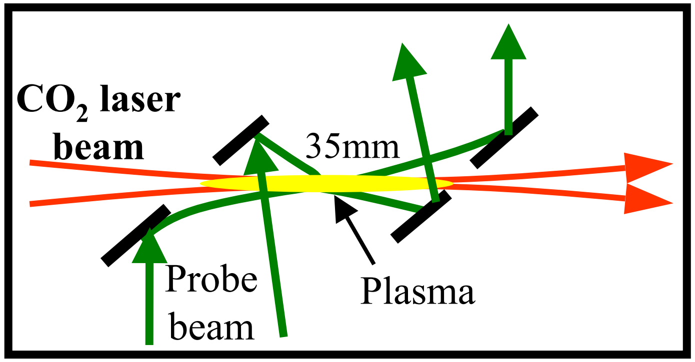


(b)

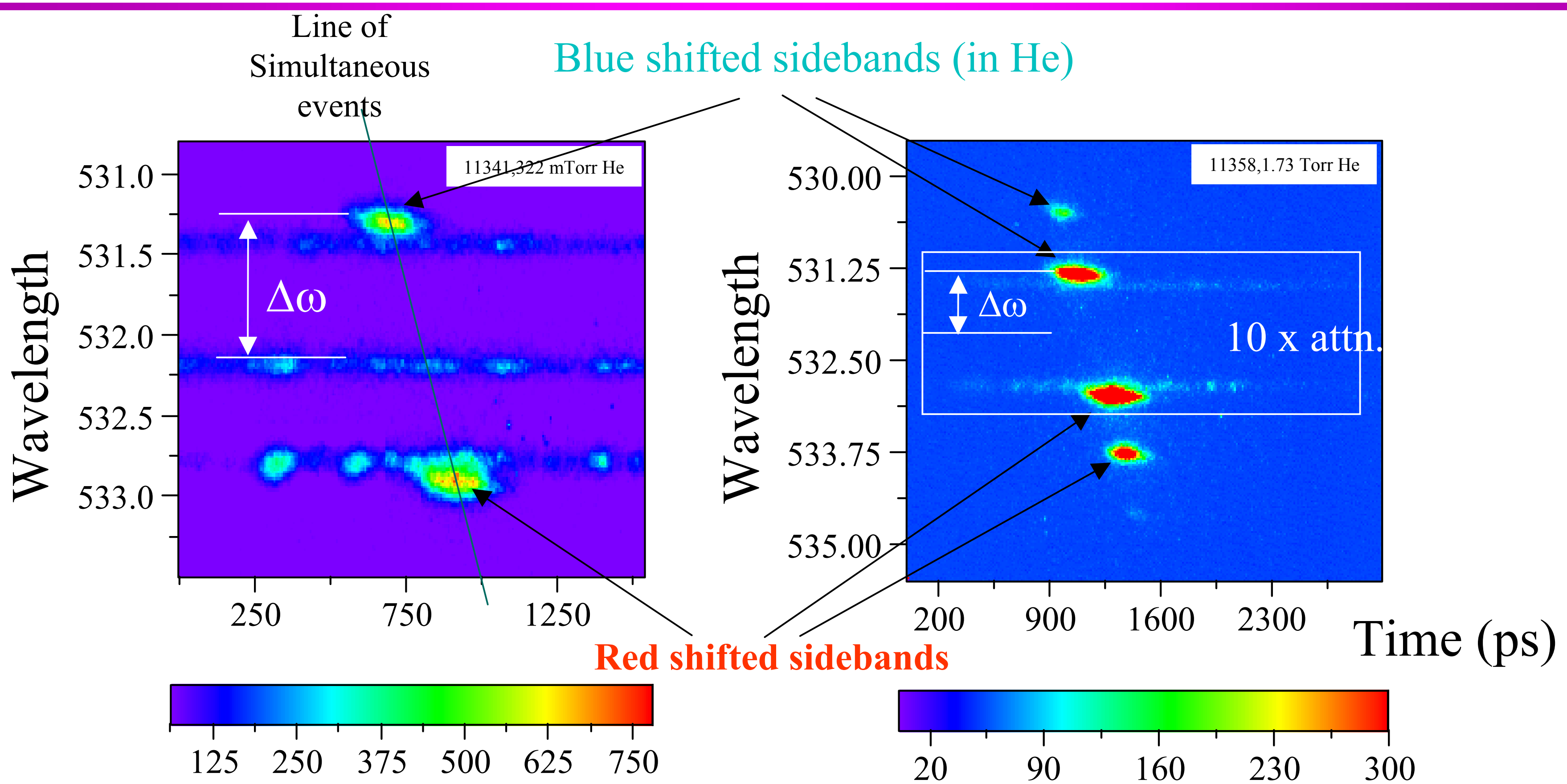
Experimental Parameters

1. **Plasma** is produced by tunneling ionization of backfill gas
   - H_2, He, Ar from 10^{15} cm^{-3} to 10^{17} cm^{-3}
2. **CO_2** laser parameters:
   - ≤100 ps FWHM, 2-λ, 10.3μm and 10.6 μm
   - energy, 10.6/10.3≅60J/25J, maximum 1 TW
   - beam size (dia.) from 1.5" to 3.4",
   - OAP focussing down to $2\ w_0 \cong 120$ μm
   - max. 6 10^{15} W/cm², linearly polarized
3. **Probe** pulse parameters:
   - visible, Q-switched, Nd:YAG, 532.1 nm
   - ~100 mJ in 5 ns, 10^{11} W/cm² in plasma
4. **Thomson** scattering parameters
   - collinear (0 degree) geometry,
     ω and k-matched
     for relativistic plasma waves
   - interaction length $\sim 2\ z_R \cong 2$ mm
   - frequency resolution 0.4 Å, time resolution ~100 ps (grating limited)





Time-Resolved Spectra From Collinear Thomson Scattering



$n = 1.07\ n_{res}$ $n = 5.76\ n_{res}$

C. V. Filip *et al.*, Rev. Sci. Instr. **74**, 3576 (2003)
also in July 2003 Virtual Journal of Ultrafast Science, http://www.vjultrafast.org.

Relativistic Plasma Wave Detection in H_2 Off Resonance

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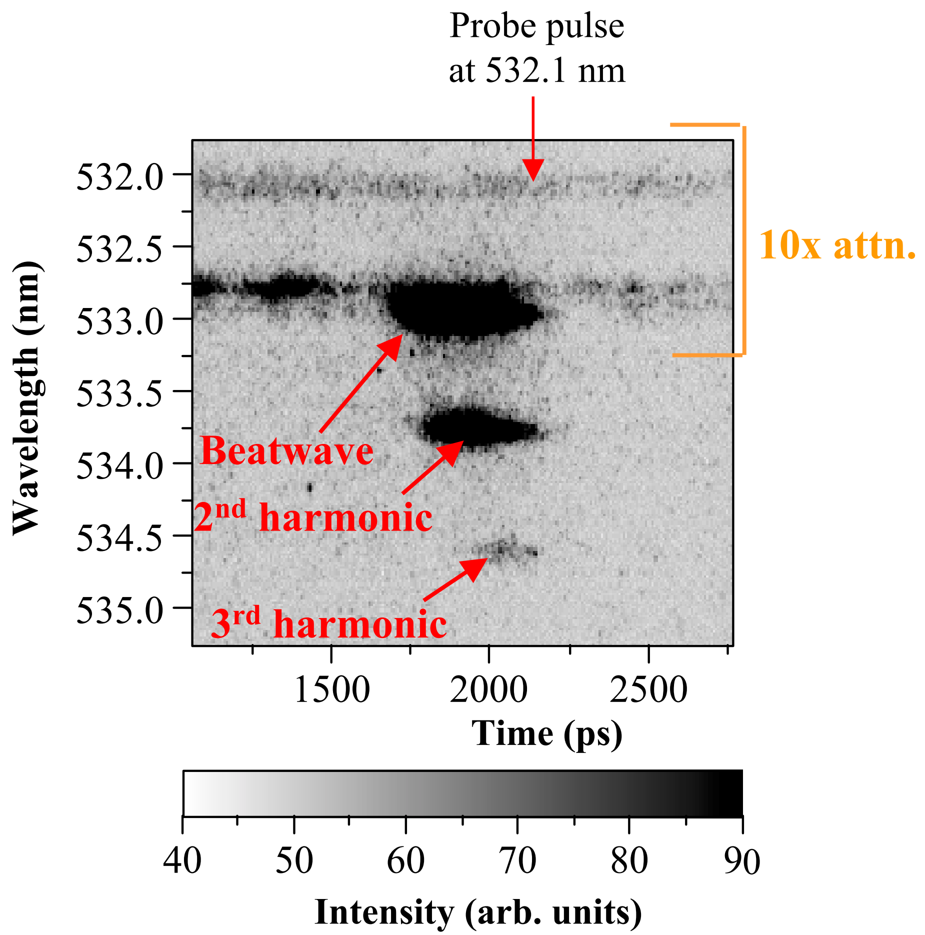
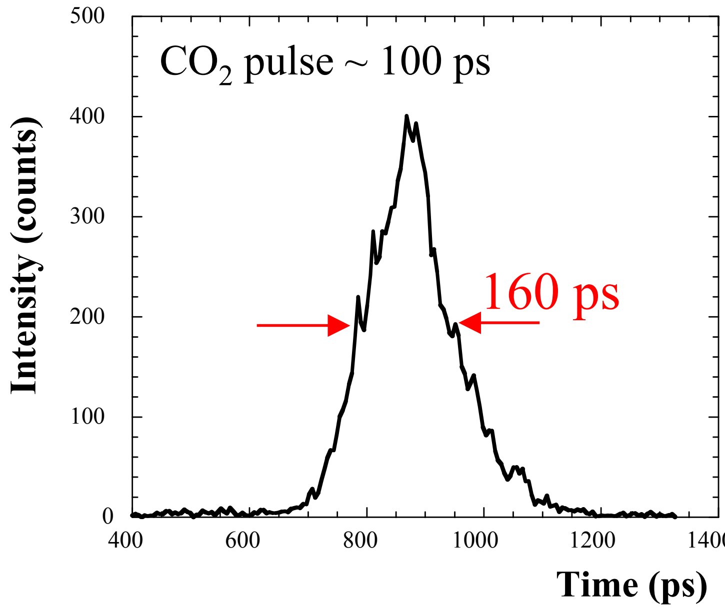
2Torr H_2; n=13.3 n_{res}



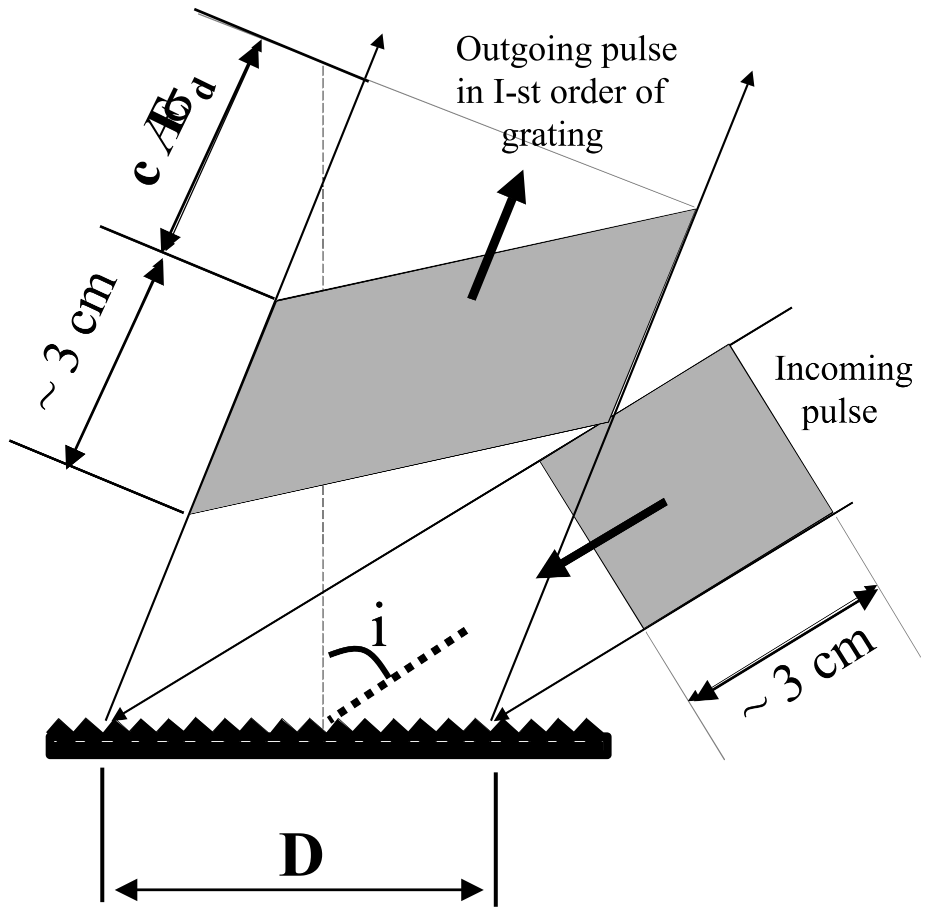
Lineout of the red shifted 2nd harmonic beatwave component



Ratio of intensity of 1st/2nd harmonic $R \cong 20$

Temporal resolution of the diagnostic system ≅ 100 ps

$$\Delta\tau_d = \frac{DN\lambda_{probe}}{c\times \mathrm{Cos}(i)} \cong 100\mathrm{ps}$$



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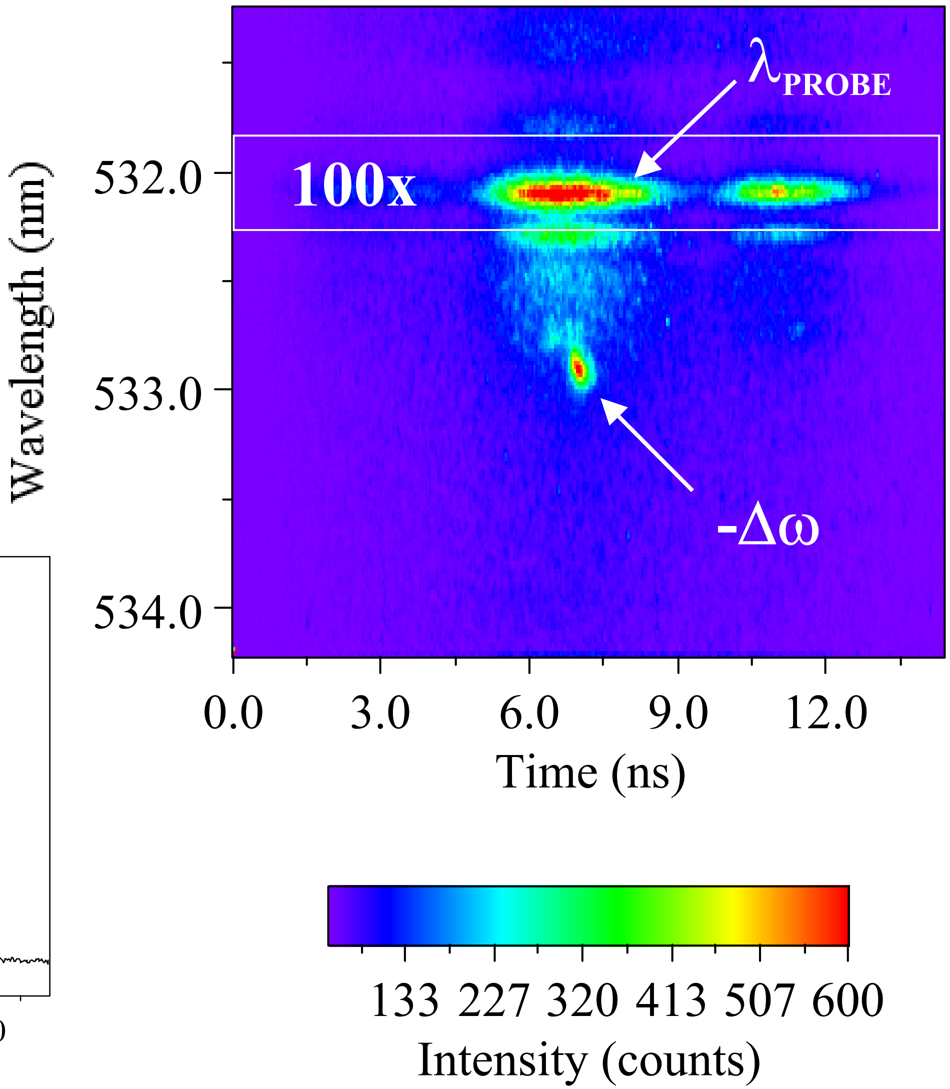
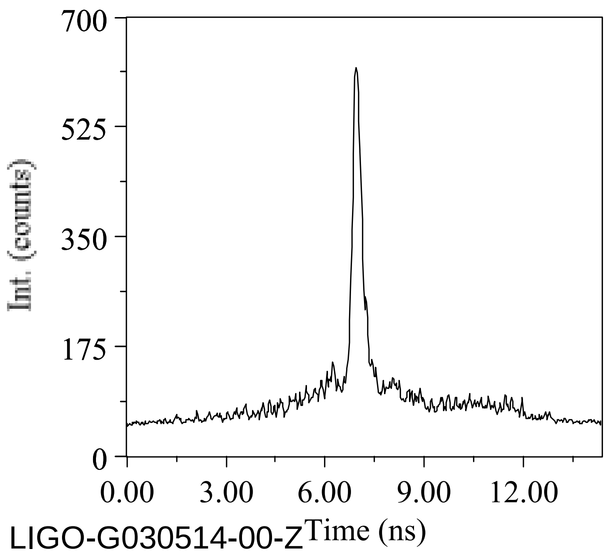
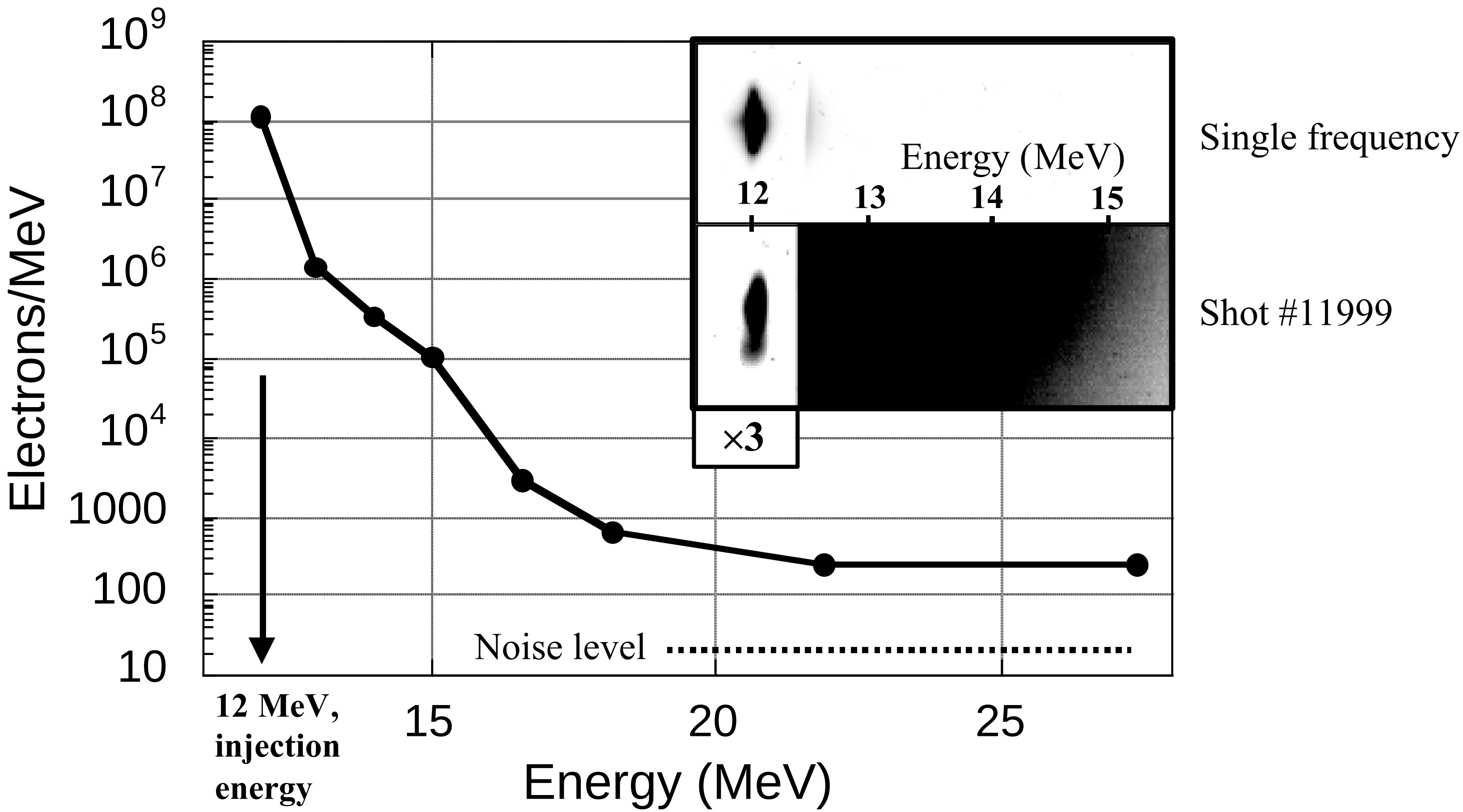
Time Resolved Spectra From F/18 Collinear Thomson Scattering, $n=n_{res}$





Acceleration of injected electrons in H_2 at $n=3.3\times n_{res}$



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Conclusions

A Thomson scattering diagnostic system has been used to detect relativistic plasma waves excited at low plasma densities (0.1% critical).

The probing was done collinearly with an independent probe laser pulse.

A novel spatial-spectral notch filter based on a triple-pass Fabry-Perot etalon was utilized to simultaneously attenuate the probe light ~10^{12} times and collect the weak, 100-ps scattered light which is shifted by only ~8 Å.

Both the red and blue-shifted scattered light up to the third harmonic was recorded in time and frequency. Using this system, non-resonantly excited plasma waves were characterized.