Optical Signatures of Relativistic Transparency in Nanometer Foils

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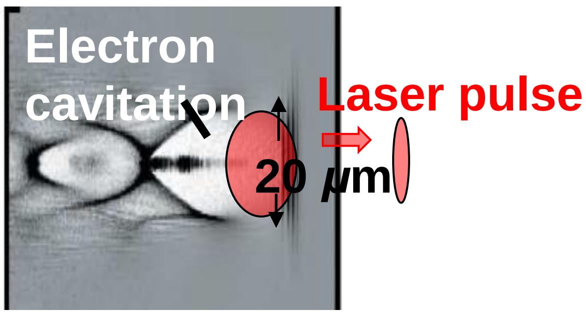
Relativistic optics: plasmas shorten and shape ultra-intense fs pulses

Light propagation depends on ratio of e$^-$ density n_e to crit. density n_c

Underdense –e$^-$ acceleration

$n_e \sim 10^{-3}\, n_c \ll n_c$, mm scale



- Laser drives cavitation
- Vel. of pulse front and rear different
- 40 fs pulse compressed to 10 fs

Faure *et al.* PRL 95: 205003 (2005); Faure *et. al.* Nature **431**: 541 (2004)

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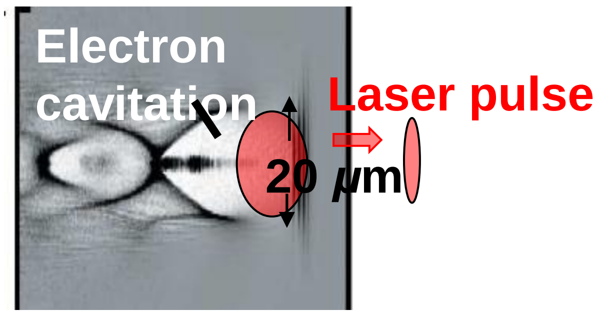

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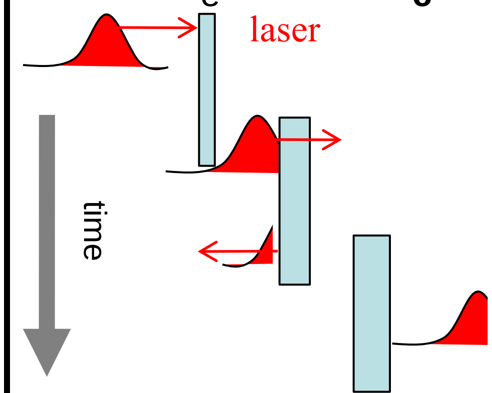
Overdense- ion acceleration

$n_e \sim 700\, n_c >> n_c$, **nm-μm scale**



- Relativistic field a_0~10 (a_0 ~1, relativistic)
- $\gamma \sim a_0$; $n_e \rightarrow n_e/\gamma$ & expansion
- Transmitted pulse shortened and shaped with relativistic signatures

Shah *et al* in prep.; Palaniyappan *et. al.* in prep.

Earlier optical study:

- **Fuchs *et al.* PRL 80: 2326 (1998**) – 30% transmission thru 2 μm, 50n_c ; Combination of hole-boring/expansion & rel. transparency

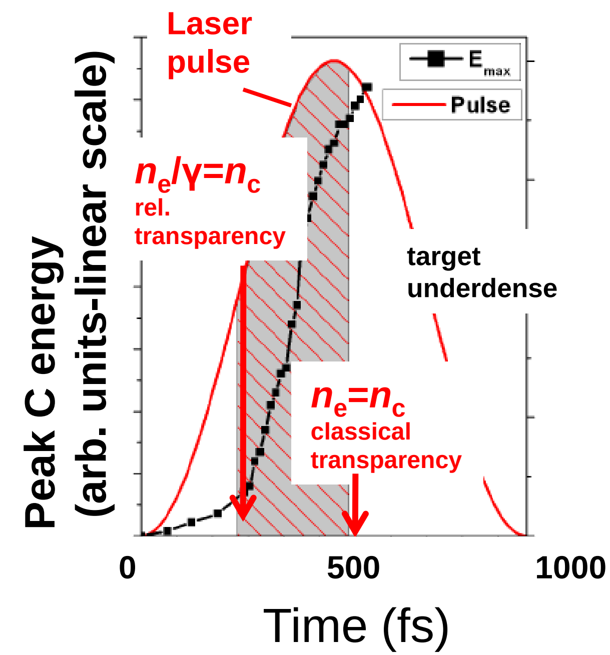
Particle based:

- **Willingale *et. al.* PRL 102: 25002 (2009)** – proton energy from varying density foams consistent with rel. trans. & hole-boring)
- **Henig *et. al.* PRL 103: 045002 (2009)** – proton energy linked to optimal onset of relativistic transparency
- **Hegelich *et. al.* submitted Nature Physics –** new regime of ion acceleration from relativistically transparent targets (Theory papers by Yin, Yan and others)

Relativistic transparency could play key role in development of laser-based particle and radiation sources

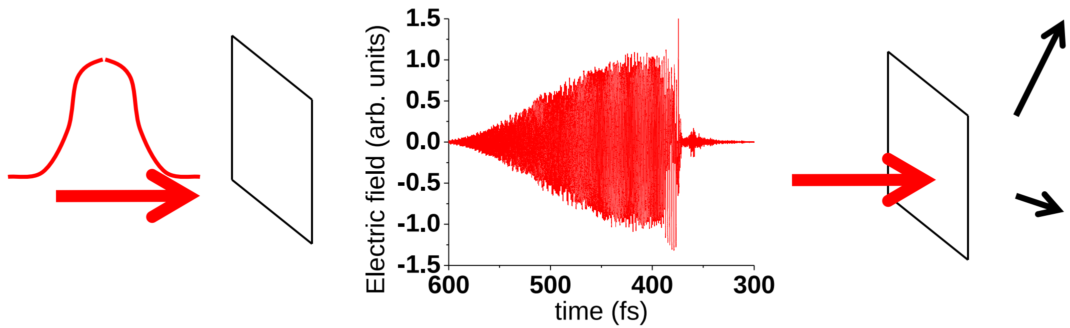
Laser-based ion acceleration

- •Thick target (µm's): laser does not penetrate but drives electrons thru target which accelerate ions
- •Ultrathin foils allow laser to penetrate overdense plasma and extend acceleration process
- •Experiments & theory show relativistic transparency critical to energy gain (right shows result of simulation for 90 J, 540 fs laser driving ions from 58 nm foil [Talk of Hegelich; Hegelich *et. al.* submitted Nat. Phys.).



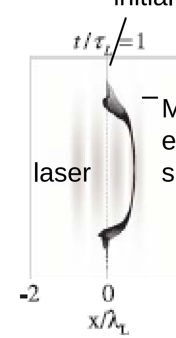
Sharp rise time to drive second foil for ….

transmitted pulse; 1D PIC (H-C Wu) using existing LANL laser conditions



Increased ion energy?

Acceleration of nm electron sheets[1]?

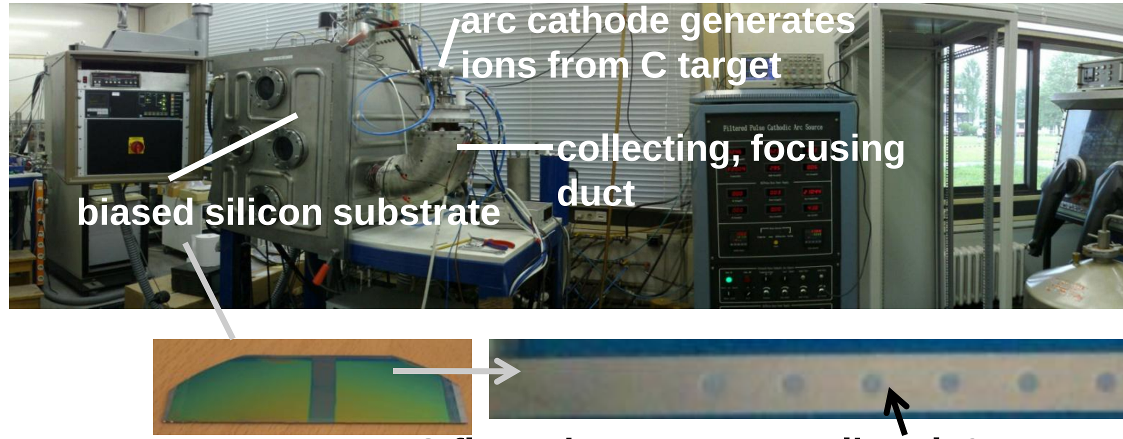


[1]Meyter-vehn & Wu, EJPD: 55: 433 (2009)

Interactions with ultra-thin sheets of solid-density plasma require nano-foil technology and temporally clean light pulses

Diamond-like-carbon (DLC)

- DLC coats tools, razors, engines
- Amorphous structure improves strength (no fracture planes)
- 3-30 nm, mm aperture (asp. ratio 1E6)
- fabricated by cathodic-arc-deposition at LMU, Munich



DLC floated onto target stalk   Φ 0.5-1 mm

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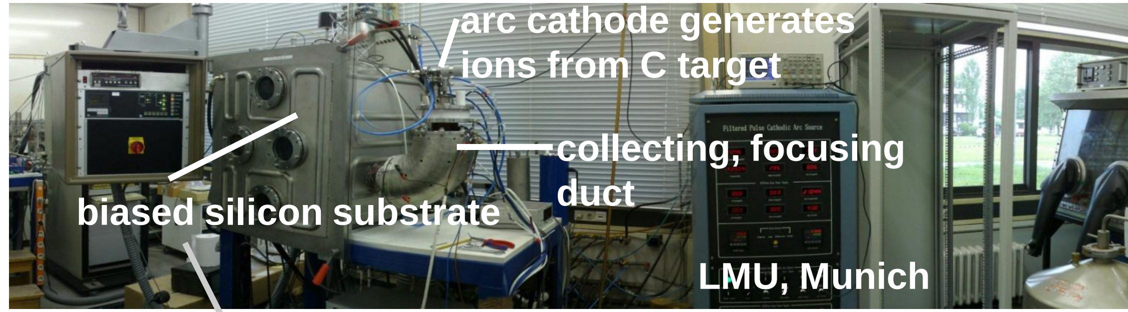

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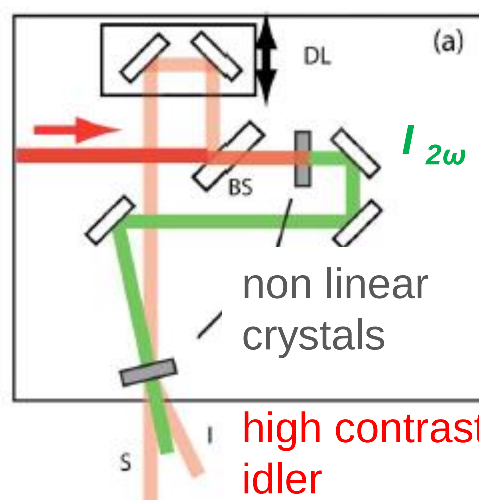
Optical parametric amplification prepulse eliminator (OPAPE)

- Peak intensity at 10^{20} -10^{21} W/cm^2 ; damage at 10^9 W/cm^2 at ns time scales
- Amplified spontaneous emission proportional to gain stages
- Remove ASE after initial 10^7 gain using idler output of saturated OPA stage



Wang and B.Luther-Davies JOSA B, **11**: 1531 (1994);
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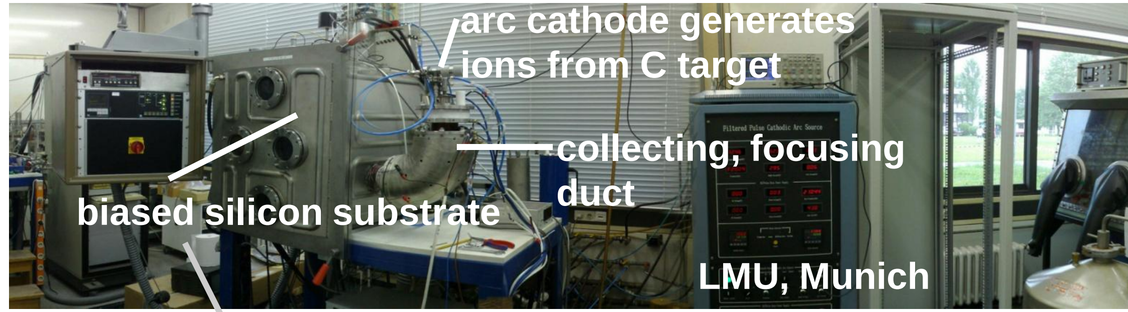

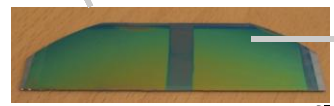

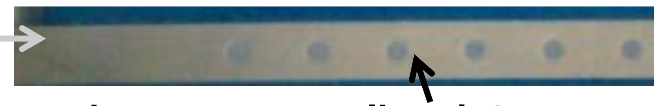

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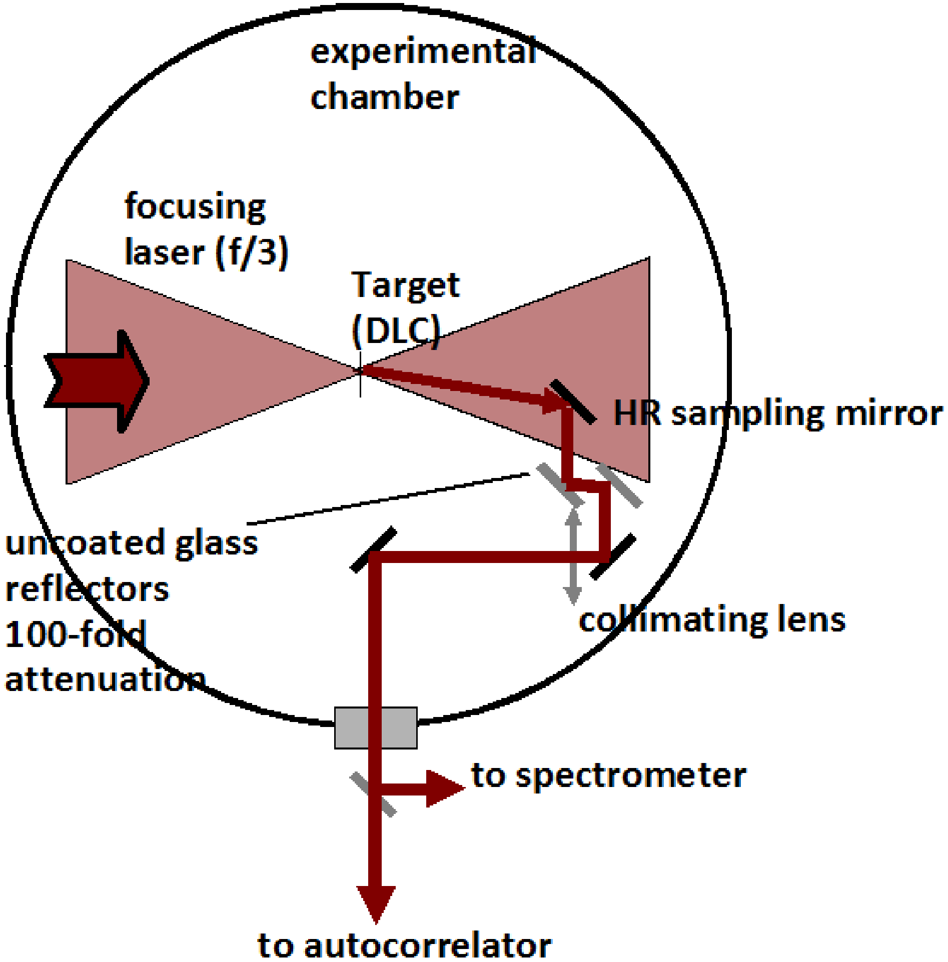
After stretching and compressing:

- better than 10^{-11} at ns timescales based on damage studies

- 10^{-9} at 100 ps ; 10^{-7} at 10 ps
- Now 10^{-9} at 50 ps

(from scanning measurements with low energy)

Setup for autocorrelation and spectral measurement of transmitted pulse



I_{pk} ~5 x10 ^{20} W/cm^2 (Φ_{FWHM} =7 μm; 500 fs; 80 J on target with 10% in central 1 μm) ; γ_{fluid} ~ 20

Glass reflectors attenuate intensity to avoid non-linear effects

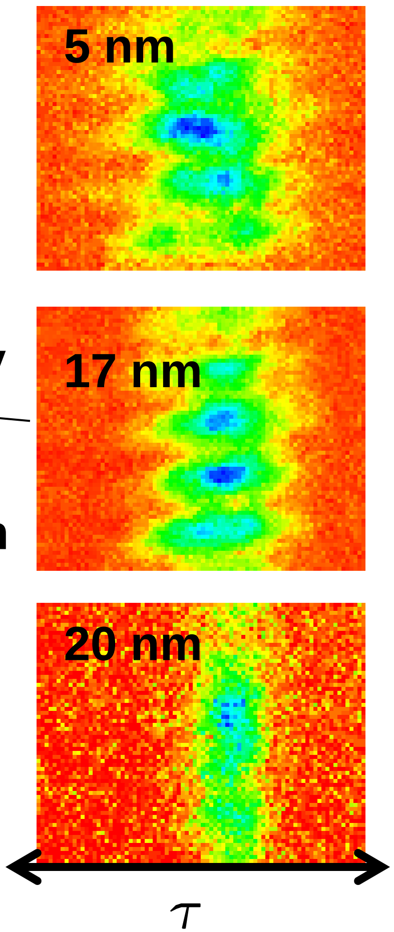
Beam collimated but not imaged

Autocorrelator aligned in front end and then single shot capable using apertures

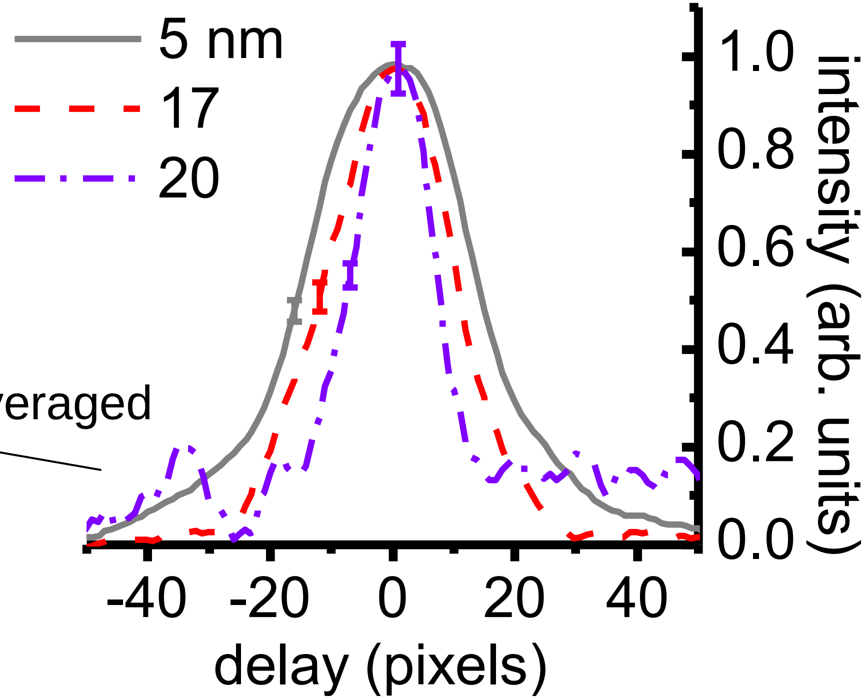
Separate autocorrelator measures incident pulse

Autocorrelations show pulse shortening of transmitted pulse

~4% efficiency in IR within 1" collection aperture



Vertically averaged lineouts



Assuming Gaussian shape….

Target	**I/P duration (fs)**	**O/P (fs)**	**Rel. change (%)**
5 nm	534 fs	534±9 fs	100±2 %
17 nm	531 fs	409 fs	77 %
20 nm	522 fs	356 fs	68 %

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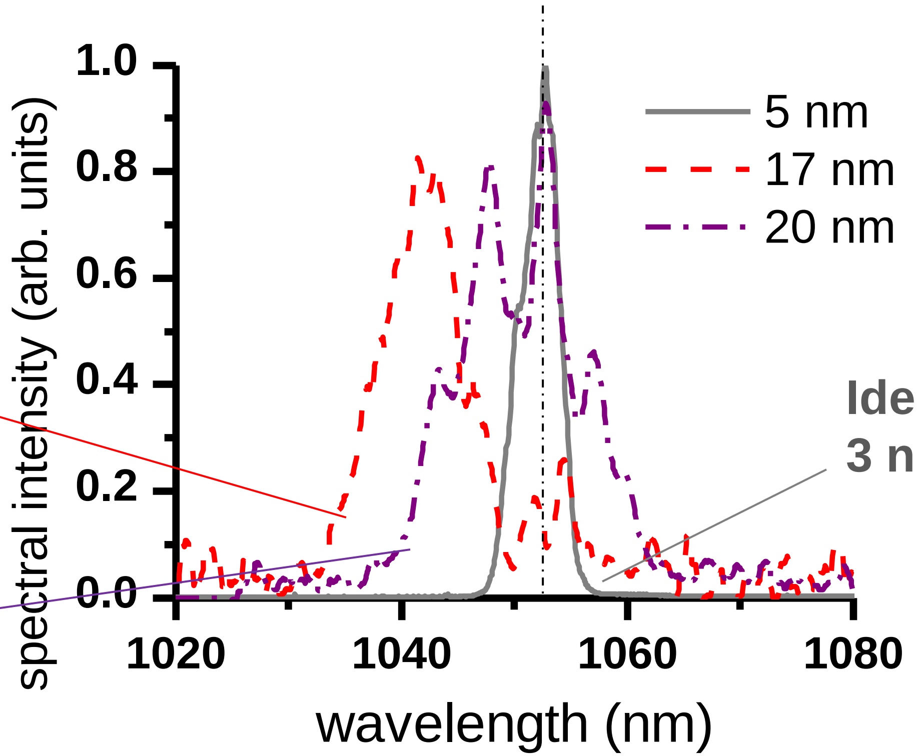
Spectra show non-transform-limited broadening, predominantly blue

77% AC narrowing;
~2.7 X BW;
4 nm centroid shift blue

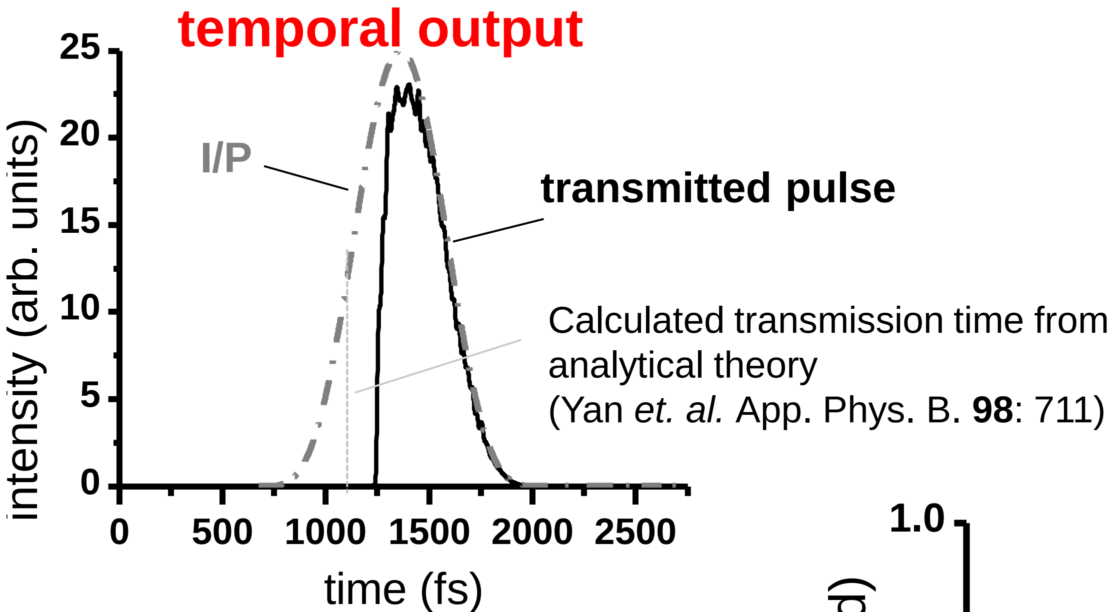
68% AC narrowing;
~3X BW;
2 nm centroid shift blue

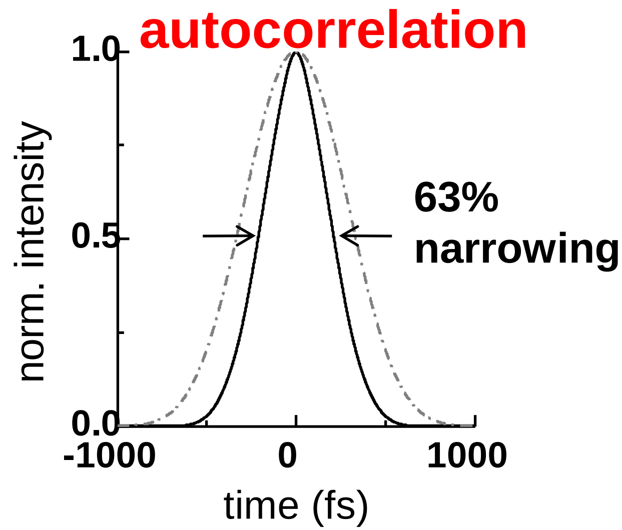


Identical to I/P;
3 nm BW

All data of Oct. 2009 run showed blue shift; April 2010 run predominantly blue shifts but some red shifts

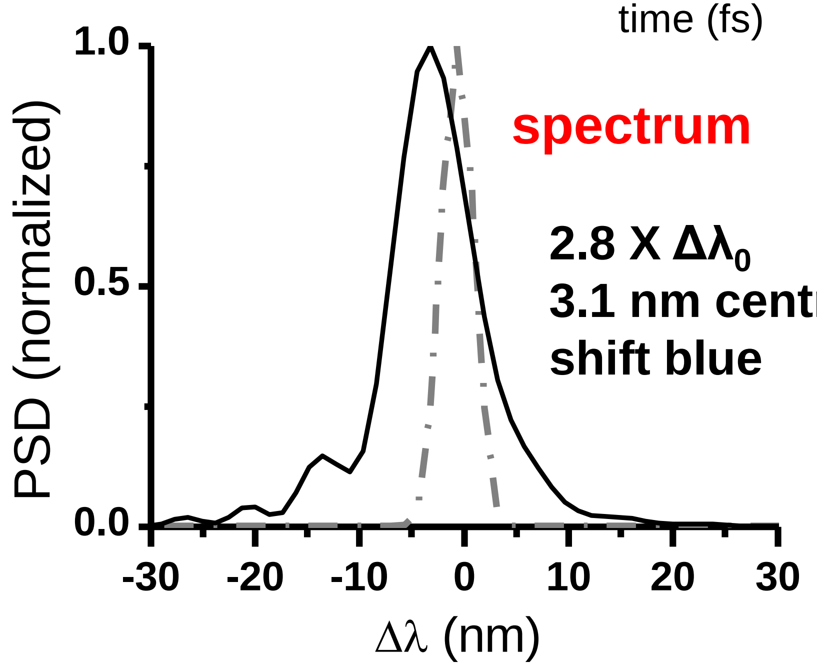
1D-PIC of transmission thru foils shows pulse shortening & spectral broadening with blue shift





Simulation parameters
a_0 =10
30 nm, 700 n_c (DLC foil)
1D,3V simulation (VPIC & Wu-PIC by HC Wu.)

50 nm shows 5.8 x $\Delta\lambda_0$ and 15.7 nm shift with only later quarter of pulse transmitting



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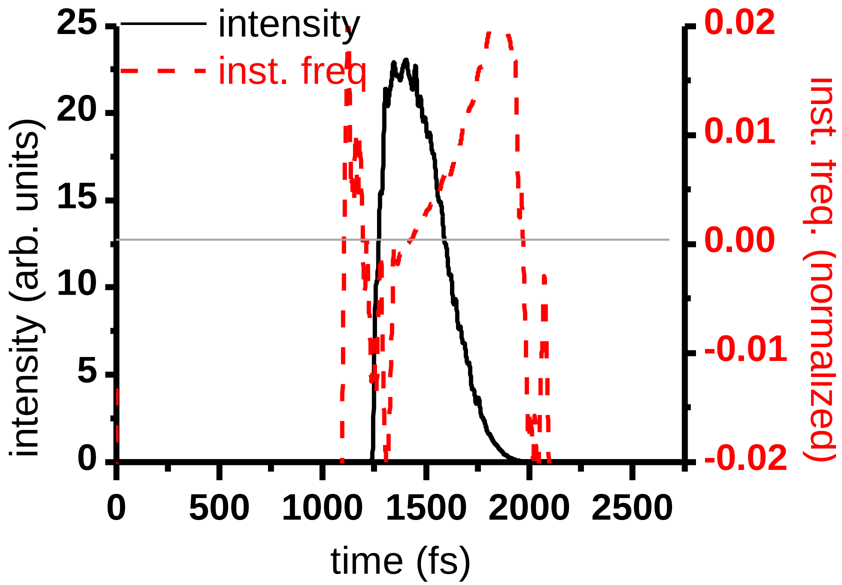
PIC shows blue-shift develops from light-speed target expansion



$$\phi = \frac{-2\pi}{\lambda}(n-1)L$$

red shift

$$\frac{d\phi}{dt} = \frac{-2\pi}{\lambda}\left\{(n-1)\frac{dL}{dt} + L\frac{d(n-1)}{dt}\right\}$$

blue shift

Instantenous frequency shows blue shift occurs on tail of pulse

Originates from time varying optical phase

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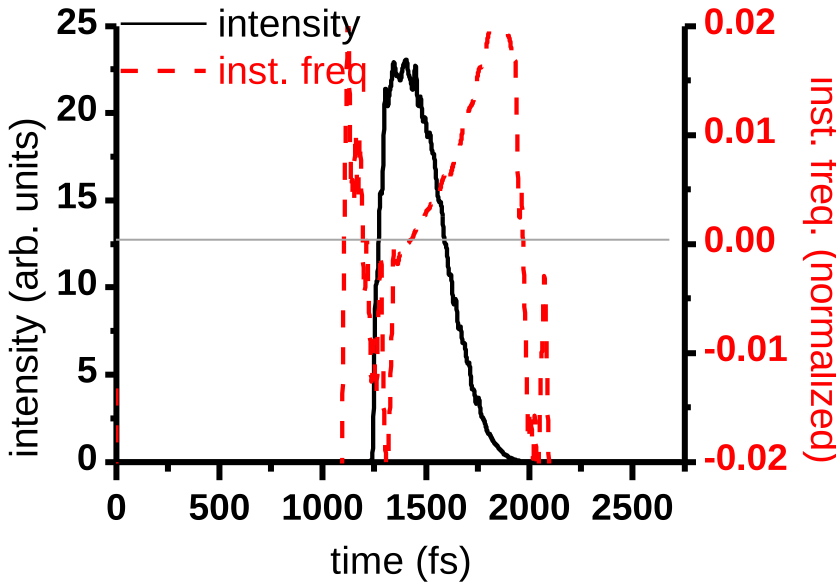

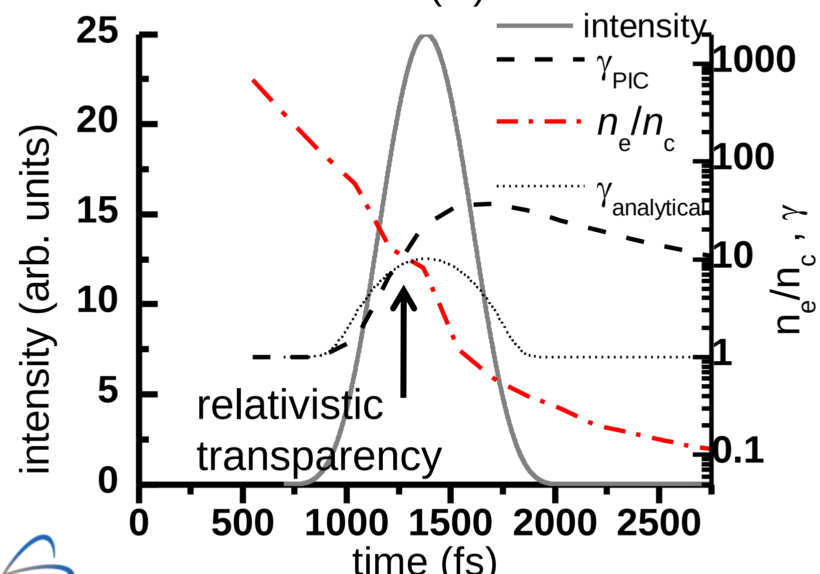

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- **Extracted <γ>, <n_e> within FWHM of density for fixed (gross) time-steps**
- **Transparency when n_e =γ (i.e. n_e/γ=1)**
- **γ initially grows similar to analytic expression**
- **After transparency, γ significantly larger and integrative--suggestive of DLA due to dephasing of orbits[1]**

[1]Meyer-ter-Vehn *et. al.* POP: **6**: 641 (1999)

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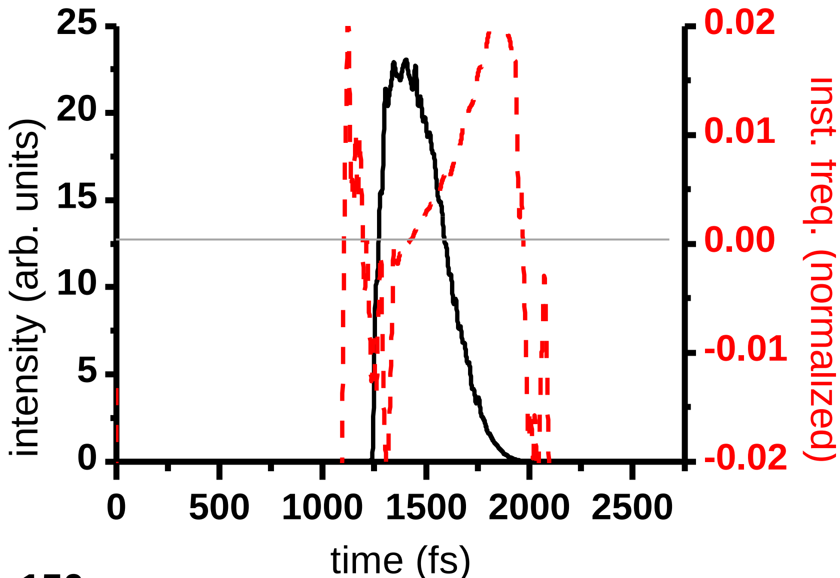

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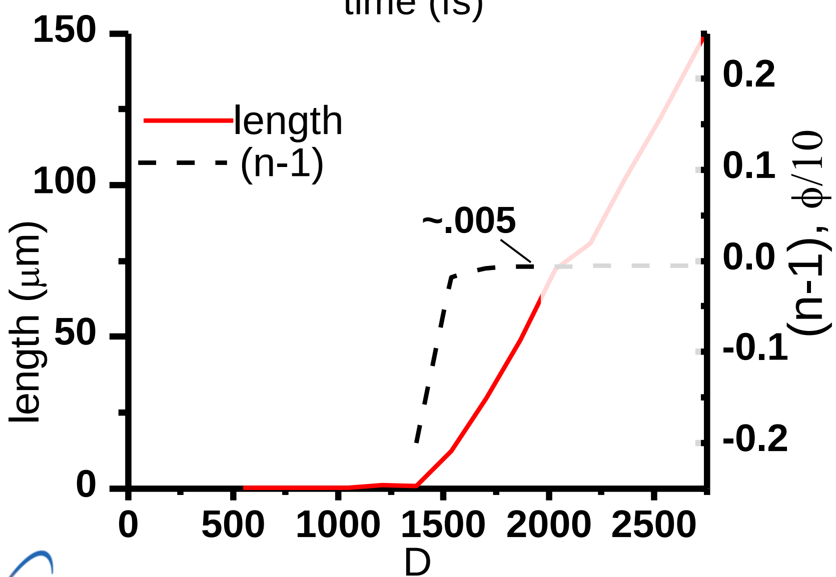

- **Extremely rapid (v~0.3*c*) length expansion following transparency**
- **Continued rise of γ and density drop rapidly brings $n=(1-n_e/\gamma)^{1/2}$ to near constant value**

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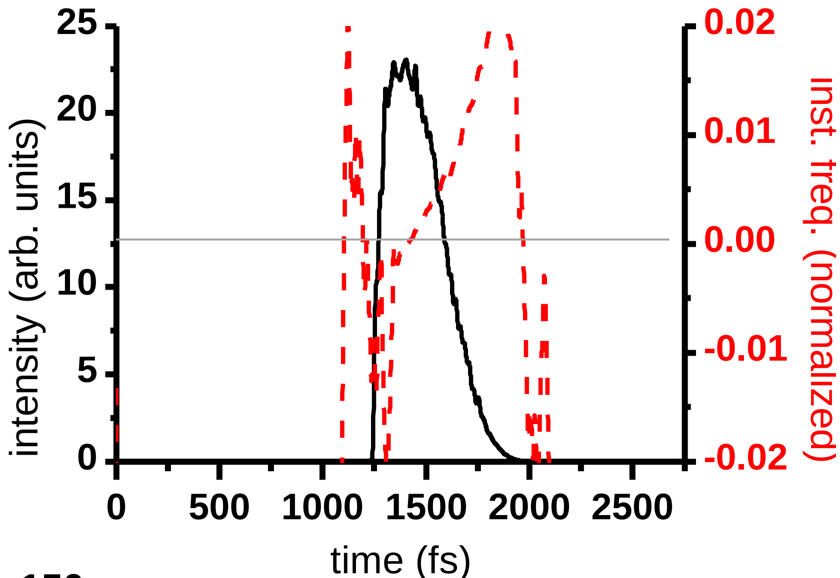

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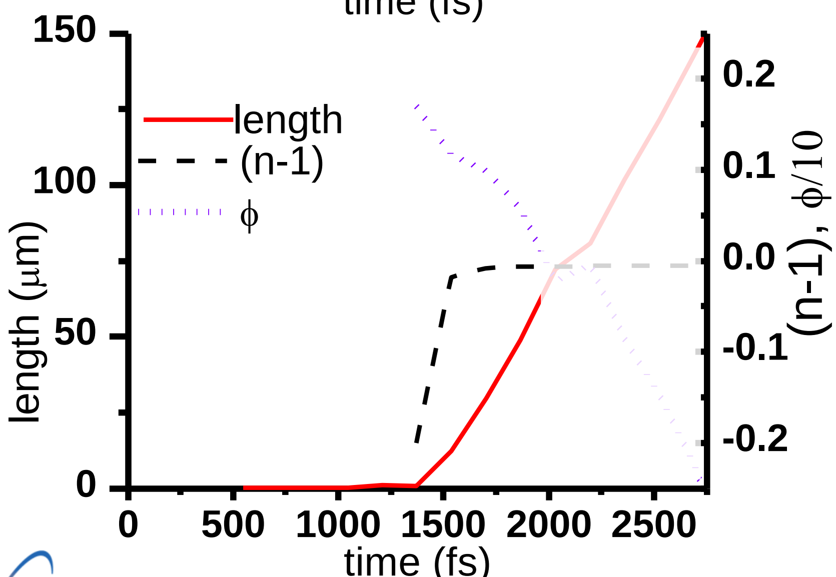
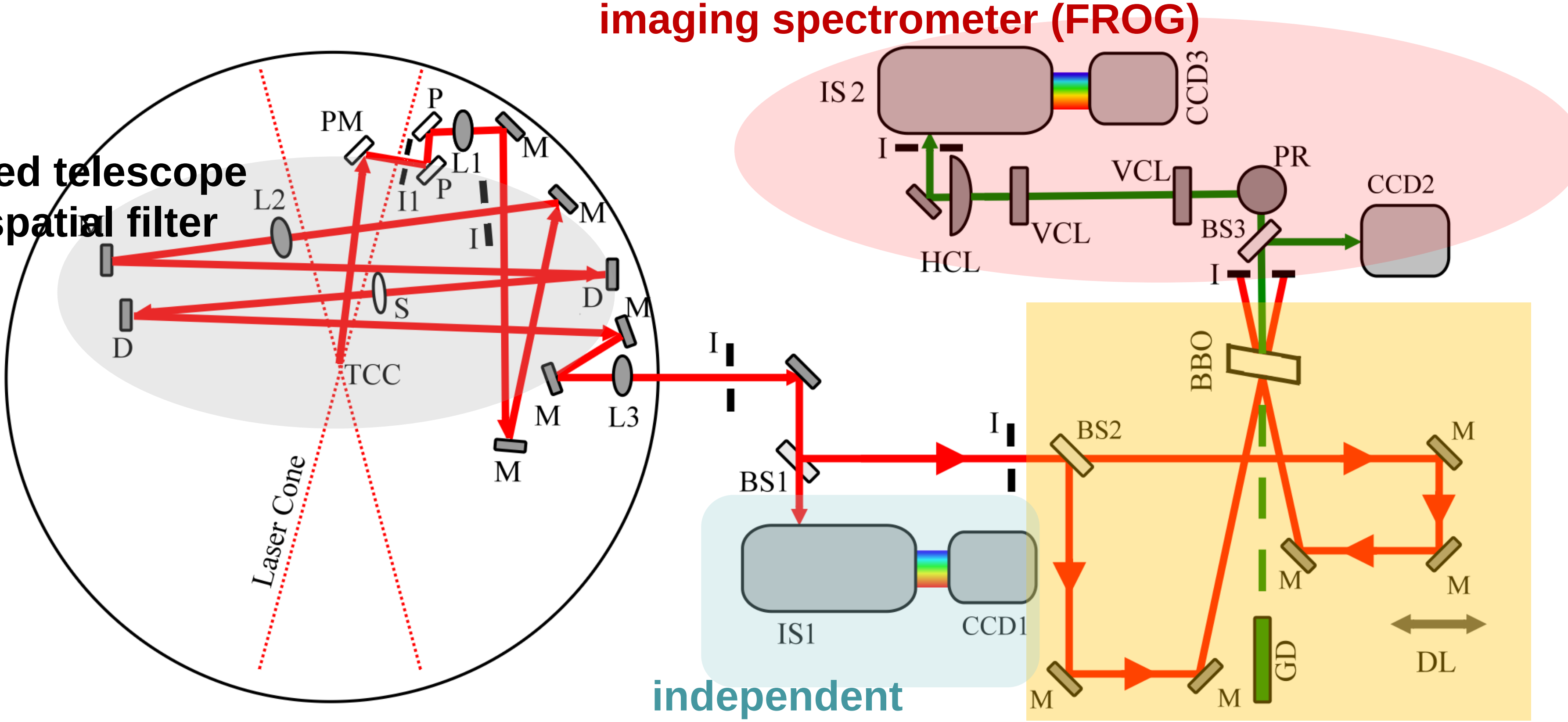


- **Early times, *L* small, d*n*/dt large gives red shift (not resolved in PIC extraction)**
- **Quickly d*L*/dt dominates giving blue shift**

Experimental setup for pulse-shape measurement

imaging spectrometer (FROG)

folded telescope
w./ spatial filter



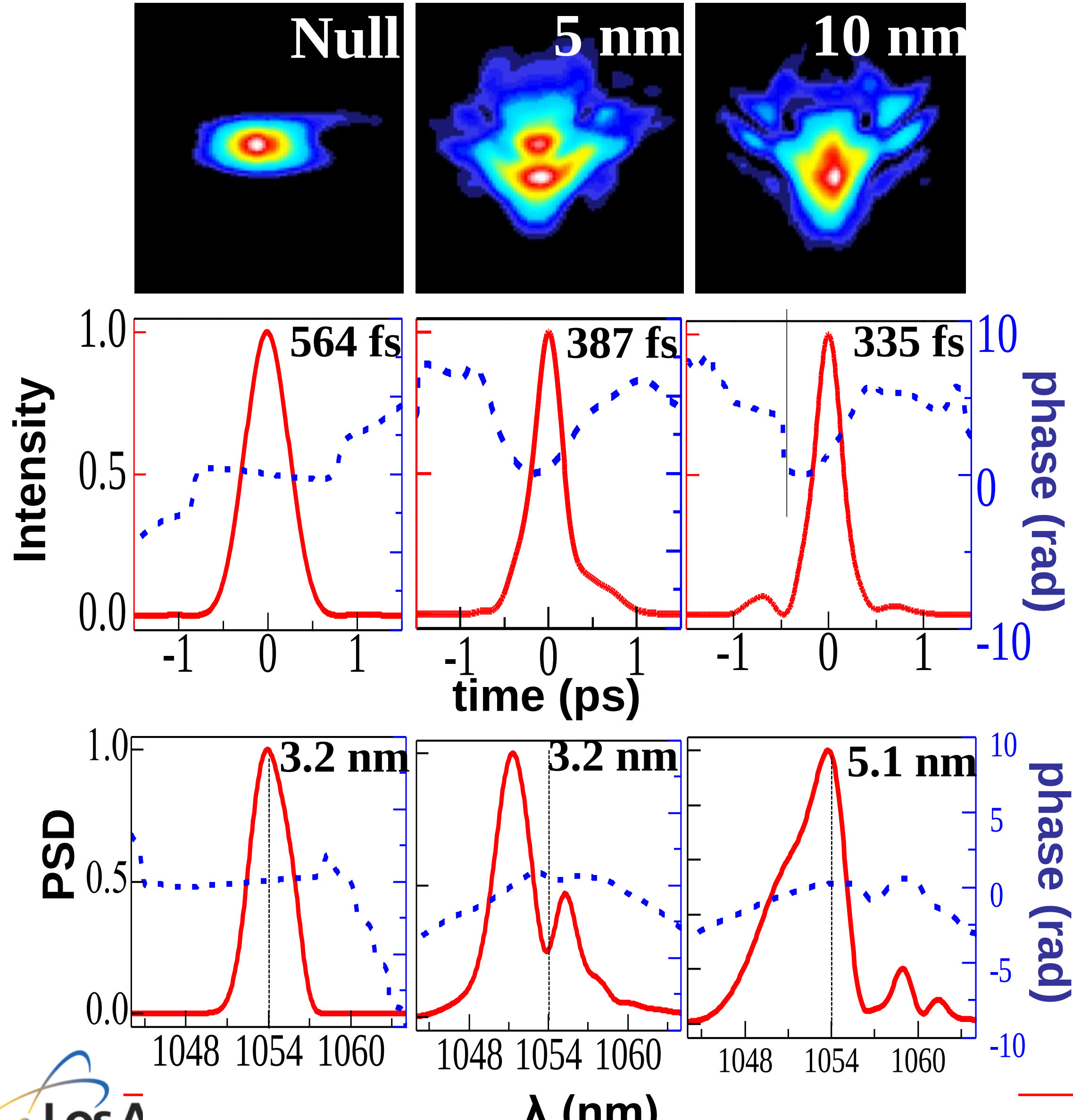
independent
spectrometer

autocorrelator

Modified autocorrelation/spectrum setup to include telescope imaging and imaging spectrometer for FROG

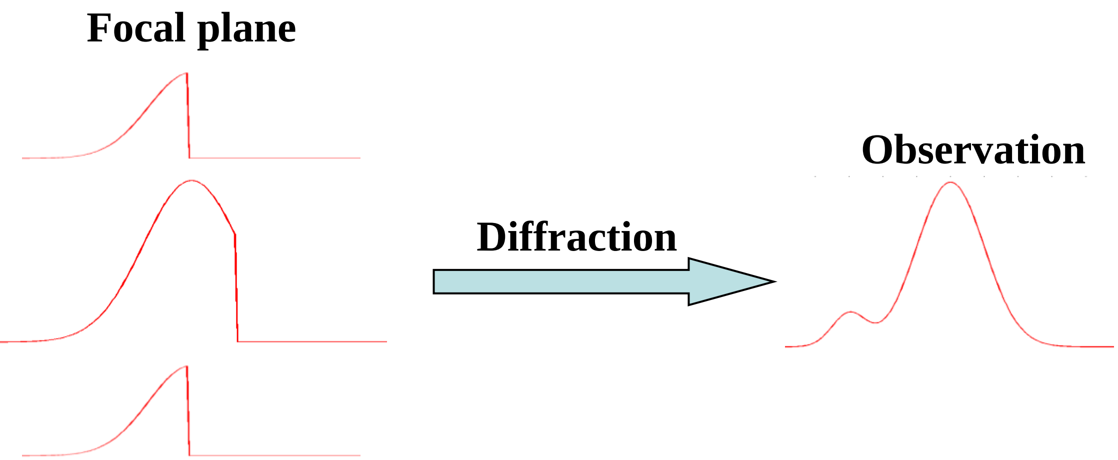
S. Palaniyappan, et al., Rev. Sci. Instrum. **81**, 1 (2010)

Pulse-shape measurements

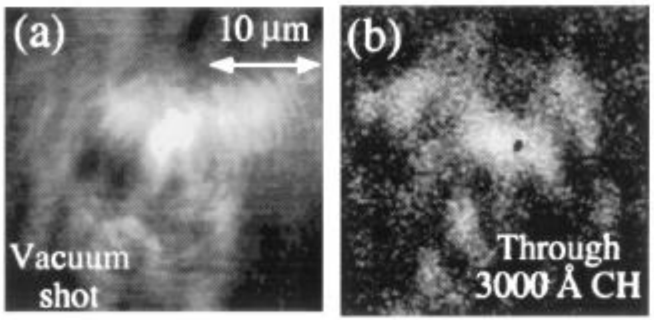


- •Pulse shortening with assymmetric shape
- •5 nm shows variability (earlier data showed no shortening)
- •Time direction selected by placing blue chirp on trailing edge as seen in PIC

Diffraction Can Blur Sharp Rise and Distort Shape



Fuchs *et al.* PRL 80: 2326 (1998)

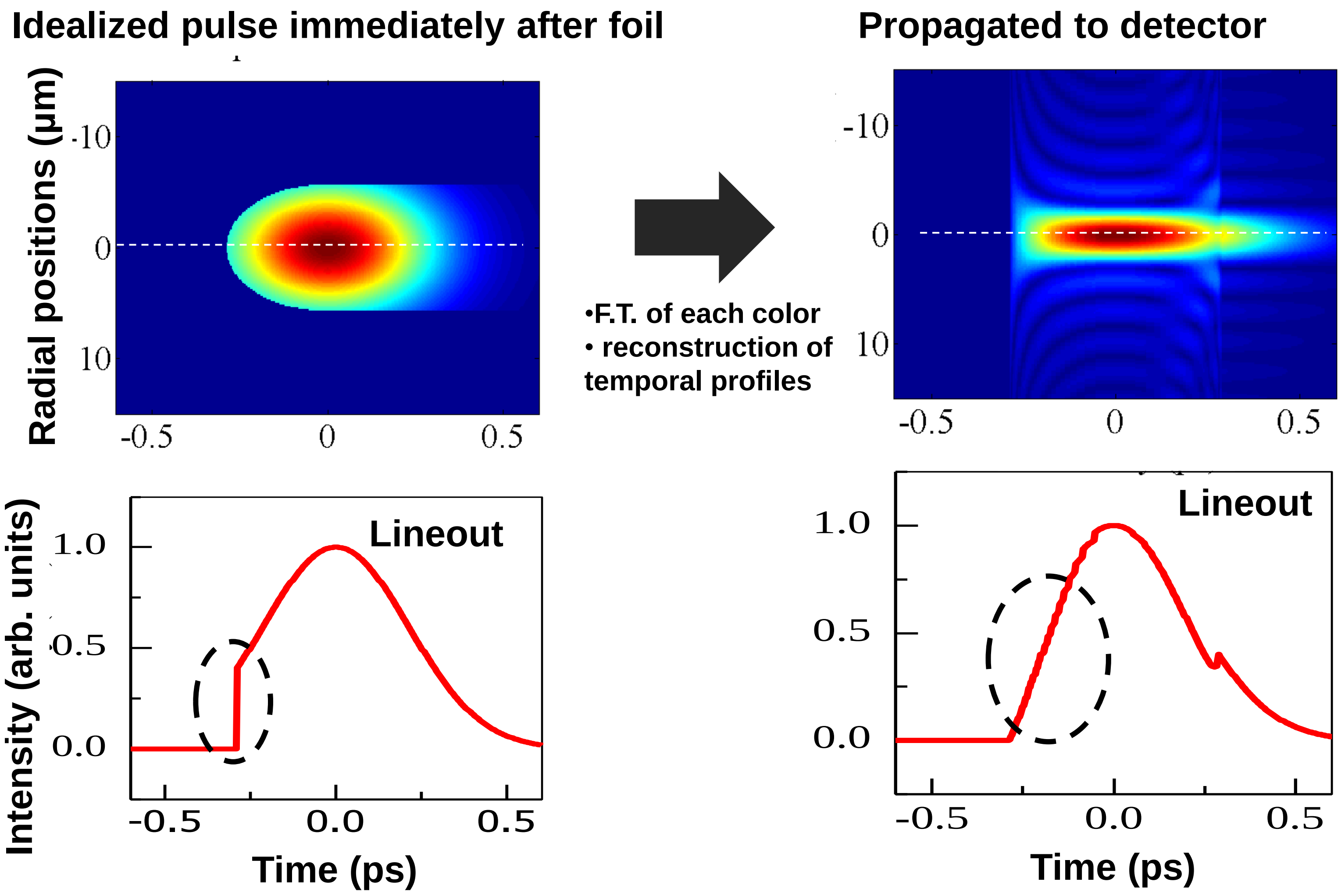


Vacuum   Thru 300 nm CH

Pulse imaged at focus

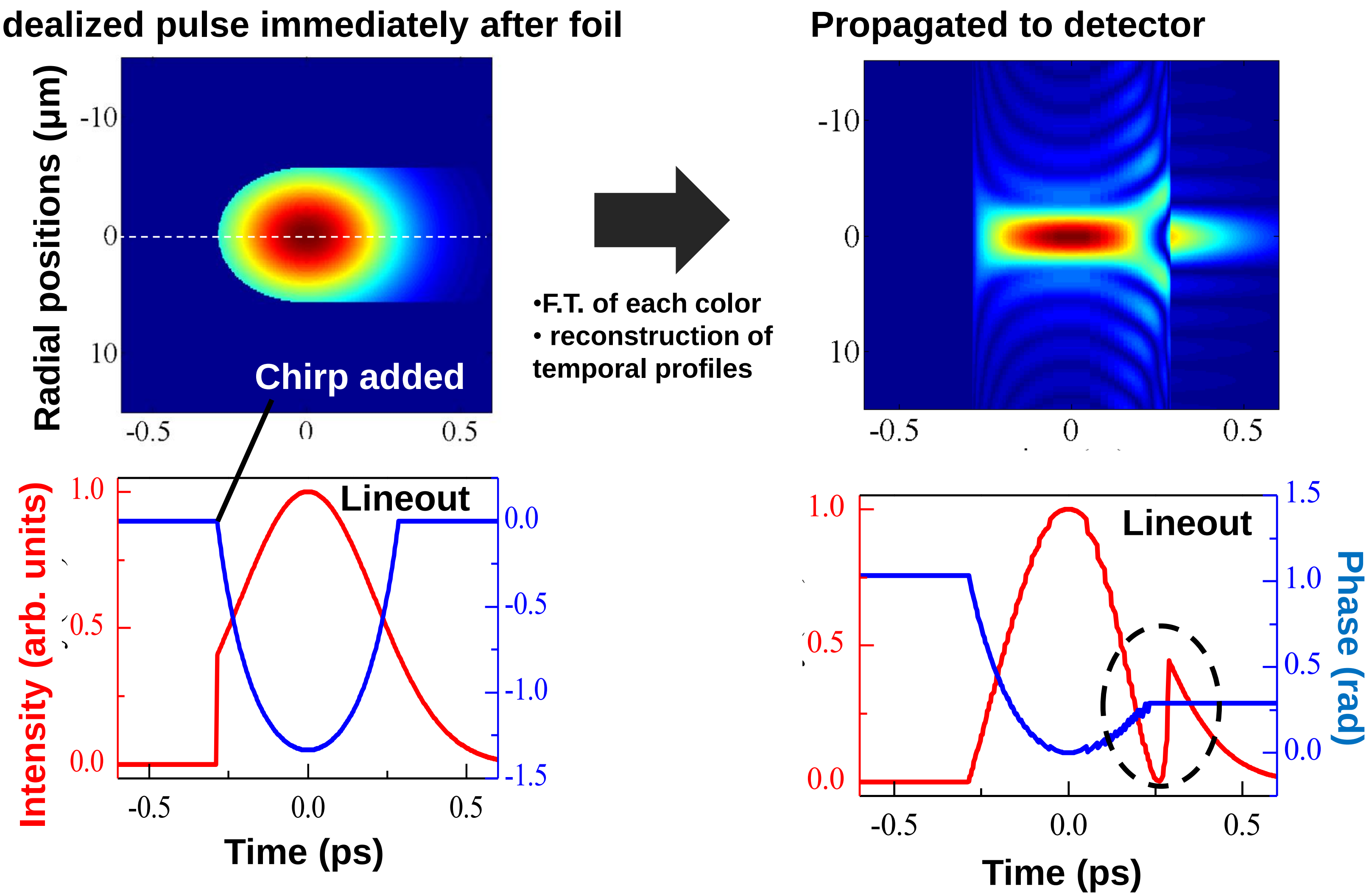
- **Fuchs *et. al.,* observed that time integrated energy varied spatially across the focal plane-- non-linearly with input profile**
- **Onset of transparency would be delayed in wings due to lower intensity and higher density**
- **Observed pulse is Fraunhofer diffraction of pulses across the focal plane. <u>Rise time lost at FROG device due to mixing of different pulses across the laser; with addition of time varying phase this also distorts pulse shape</u>**

Loss of Rise Time due to Diffraction



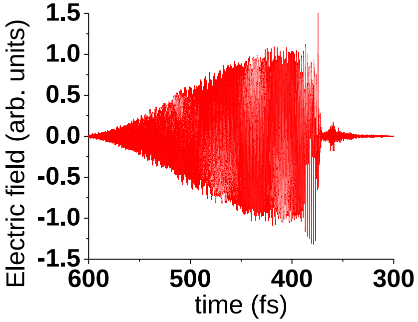
Spatial variation of transmission time results blurs sharp rise on propagation

Pulse distortion due to diffraction when chirp included



Spatial variation of transmission time + chirp results in additional distortion

Summary: Optical signatures of relativistic transparency in nm foils using high-contrast Trident Laser



•Autocorrelation of transmitted light shows expected signature of pulse shortening due to induced transmission

•Spectra show blue shifting consistent with simulation in which mechanism is traced to rapidly expanding target

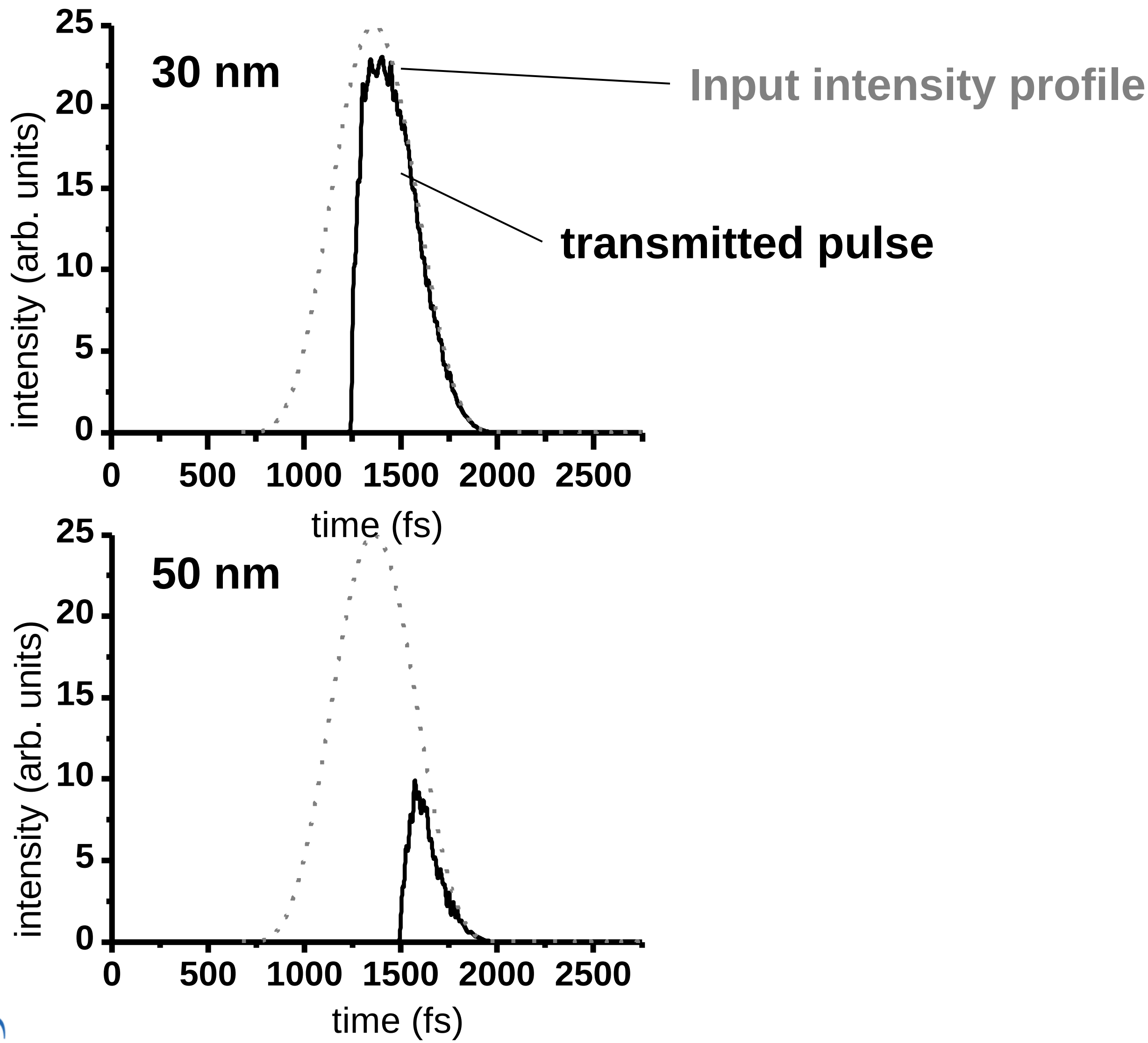
•Pulse shape measurements using FROG show asymmetric, shortened pulses consistent with propagation of spatially varying shaped pulses to detector

•Use assumptions relating density with length & γ with intensity, to recover temporal evolution of density (n_e (t)) from measured inst. freq.

•Approaches which eliminate diffractive effects to allow recovery of actual rise time for applications of shaped pulses

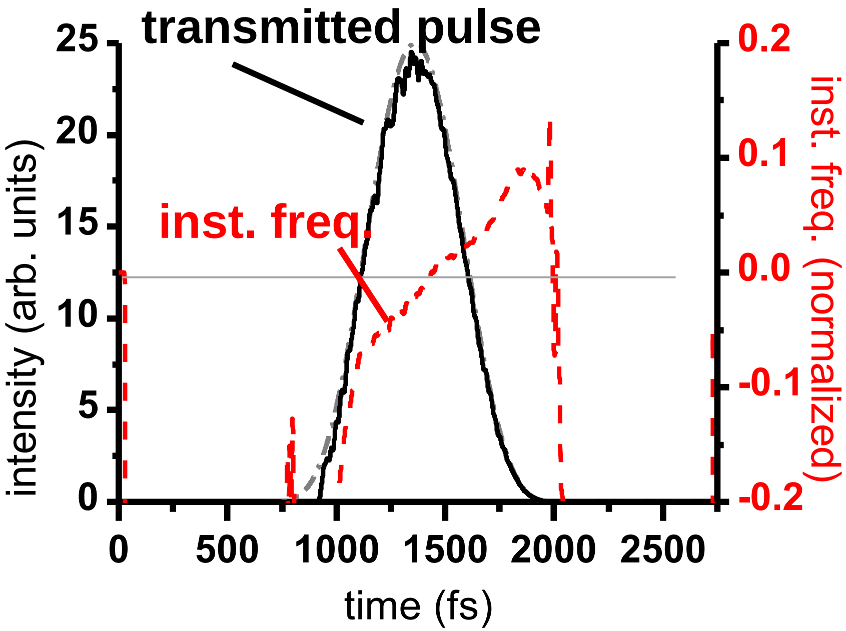
Extra slides

1D-PIC of transmission thru 30 nm and 50 nm foils shows pulse shortening & spectral broadening with blue shift

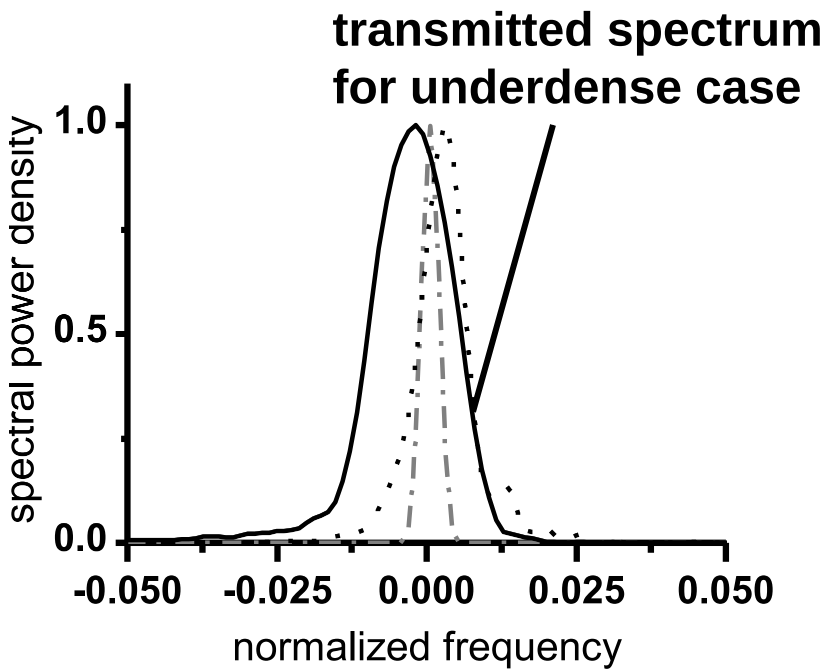


Simulations run by Hui-chun Wu using VPIC and Wu-PIC
a

Underdense target leaves intensity envelope unchanged and generates red and blue colors from self-phase-modulation



30 µm, 0.7 n_c
All pulse transmits, thus both rising and falling edges present and obtain red and blue colors



Spectrum broadens due to chirp of self-phase-modulation while temporal profile is unchanged. Could we exploit this?

Additional slide