# *Energy scaling of hollow-fiber frequency conversion of ultrafast pulses*

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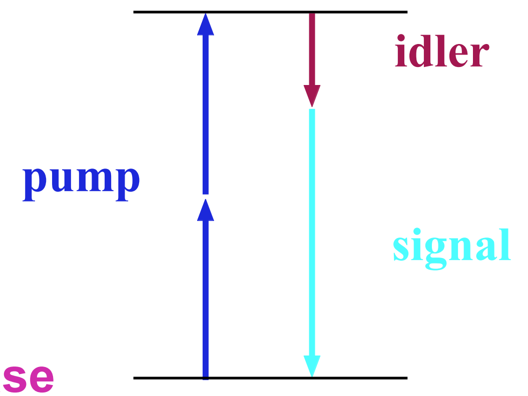
# Hollow fiber frequency mixing

## Gas as nonlinear medium:

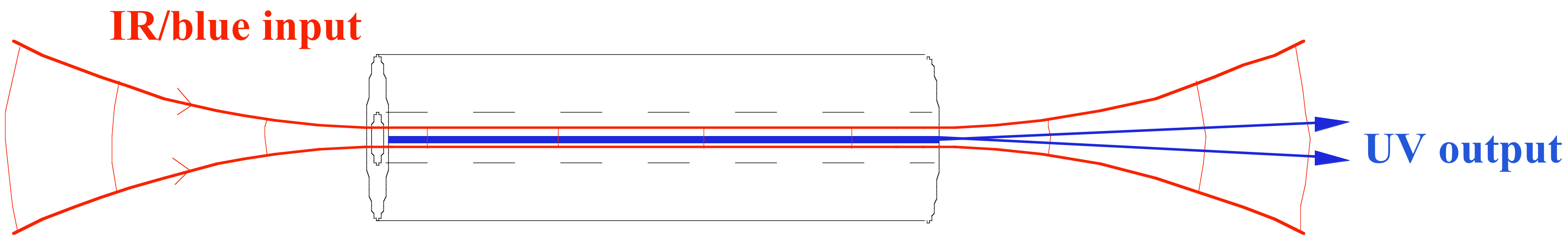
- low dispersion
- supports high intensity
- third-order mixing

## Use capillary to guide pump beams:

- increase interaction length
- Phase-matching of conversion:
  tune pressure to balance gas/waveguide phase

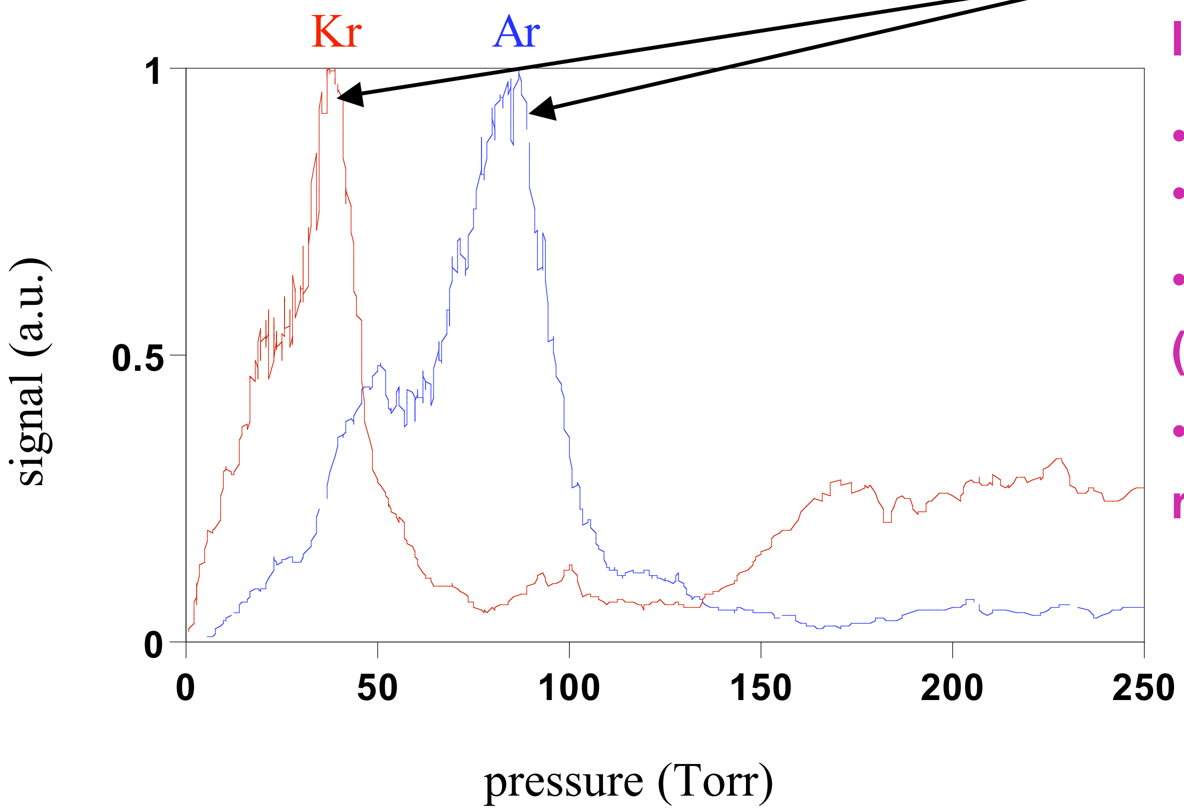


$$\omega_{signal} = 2 \times \omega_{pump} - \omega_{idler}$$



Durfee *et al,* Optics Letters **22**, 1565 (1997)

# Earlier mixing results:

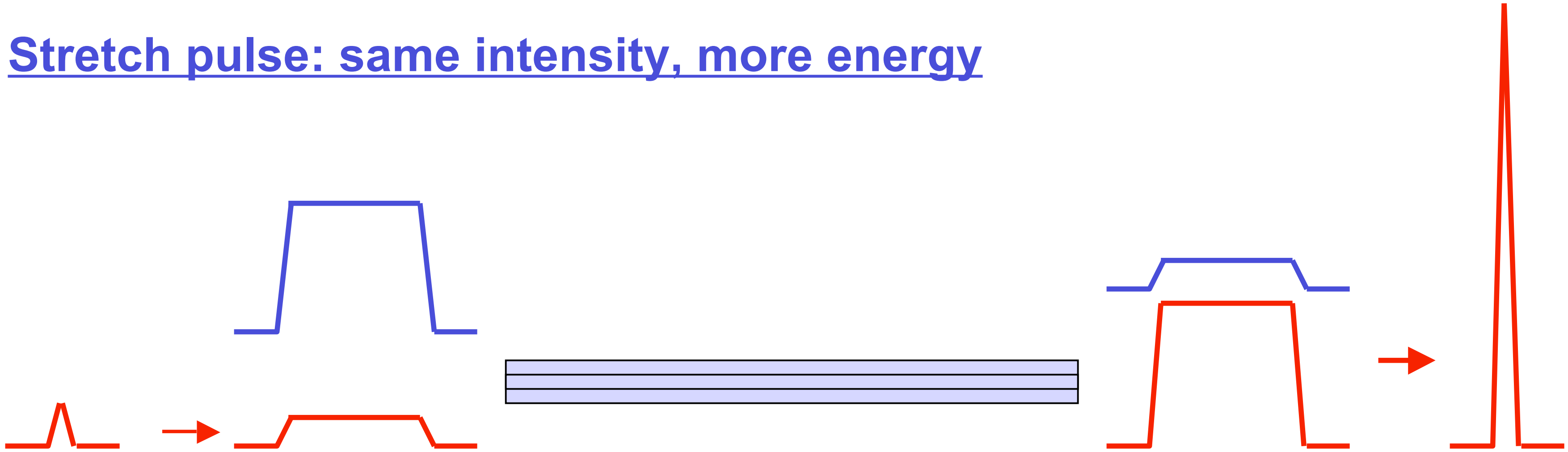


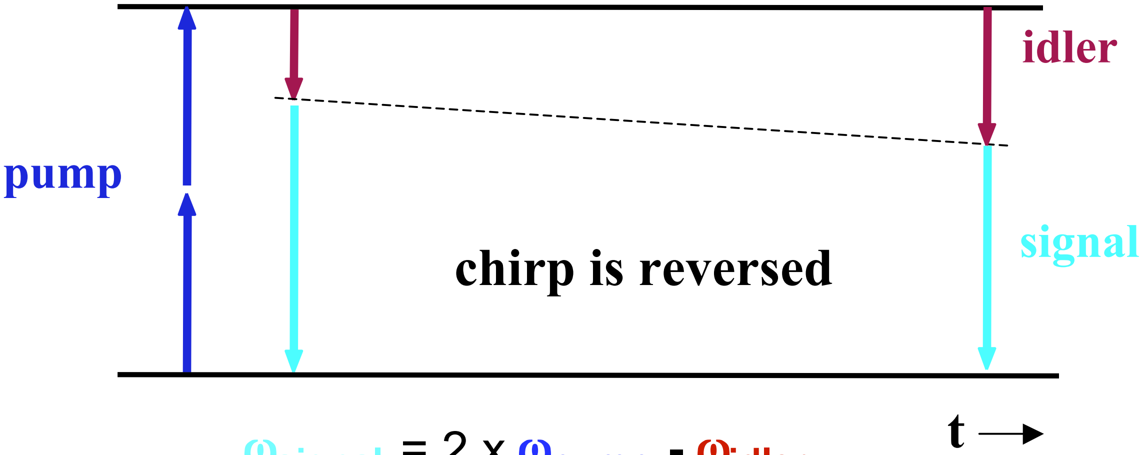
- pressure optimum produces lowest-order $HE_{11}$ UV mode
- XPM can *broaden* bandwidth
- compress to 8fs
- high conversion efficiency (40% from pump)
- output energy in the 1-5μJ range

**Energy limitations: ionization, cross phase modulation**

# OP-CPA: optical parametric chirped pulse amplification

## Stretch pulse: same intensity, more energy

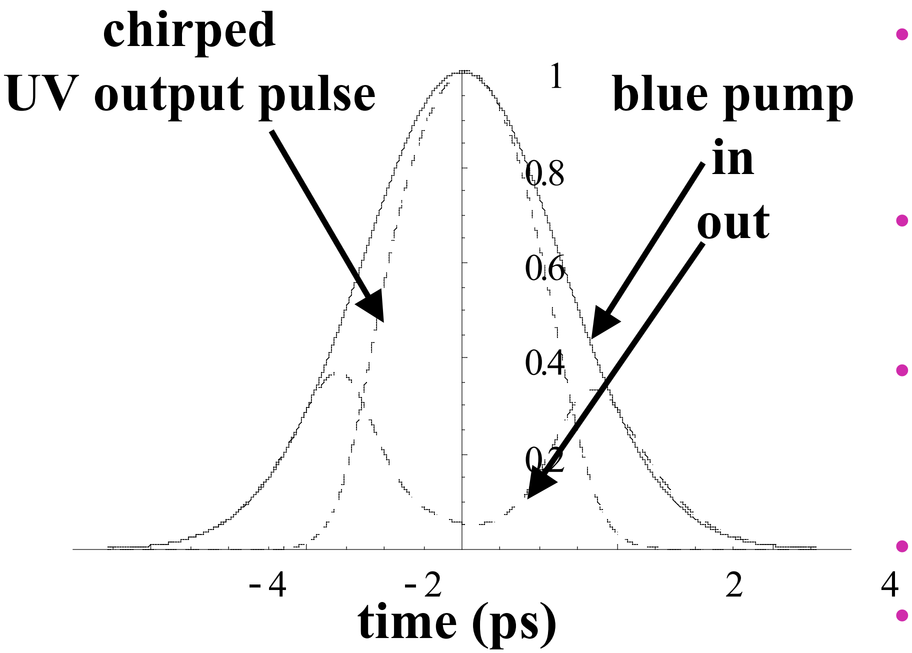




$$\omega_{signal} = 2 \times \omega_{pump} - \omega_{idler}$$

# OP-CPA: conversion simulations

## Saturated conversion without gain-narrowing is possible



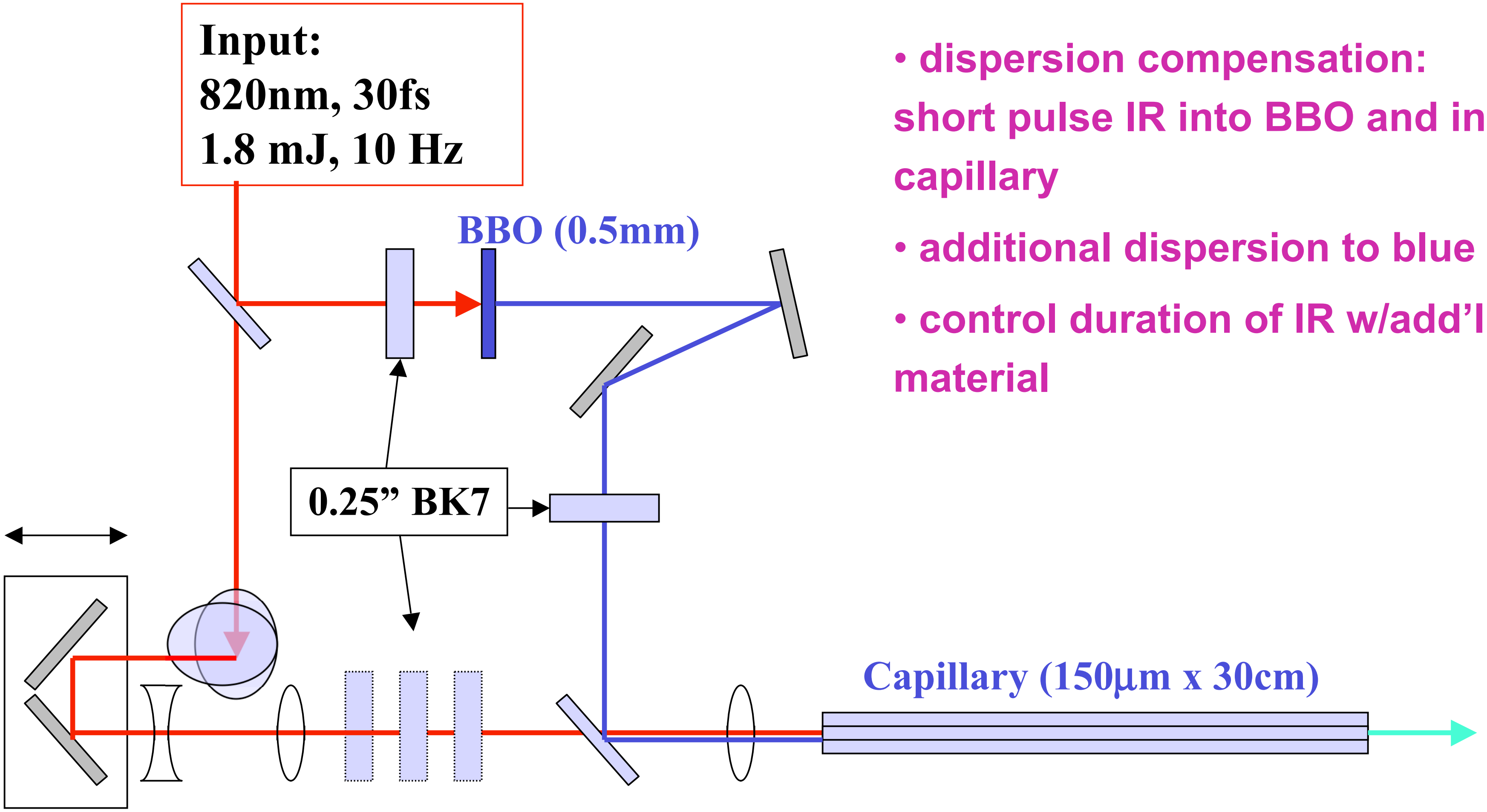
- low gain for seed
  → low degree of gain narrowing
- wide-band or narrow-band pump
- third-order process
  → generate new wavelengths
- high output beam quality: single mode
- but requires high input beam quality for efficient waveguide coupling
- output spectrum is not narrowed

<u>Shown here:</u>
4ps pump, 1.8mJ
50% conversion to UV

# Comparison of amplifier technologies

| | Laser crystal amplifiers | OP-CPA (crystals) | OP-CPA (hollow fiber) |
|---|---|---|---|
| •energy storage | ✓ | x | x |
| •ASE/prepulses | ✓ | x | x |
| •gain-narrowing | ✓ | ✓ | x |
| •thermal loading | ✓ | little | x |
| •dispersion | ✓ | little | x |
| •B-integral | some | little | little |
| •amp $\lambda$ | limited choice | $\lambda_a>400$ | $\lambda_a>100$ |
| pump req'ts | | | |
| •pump $\lambda$ | limited choice | $\lambda_p>355$ | $\lambda_p>200$ |
| •duration range | wide | <1ns | <100ps |
| •shape | any | flat-top | gauss, flat |
| •beam quality | gauss-flat | flat | gauss |
| •alignment | easy | overlap, angle | mode-matching |
| •bandwidth/phase | any | narrow | narrow or chirped |

# Hollow fiber OP-CPA: experiment

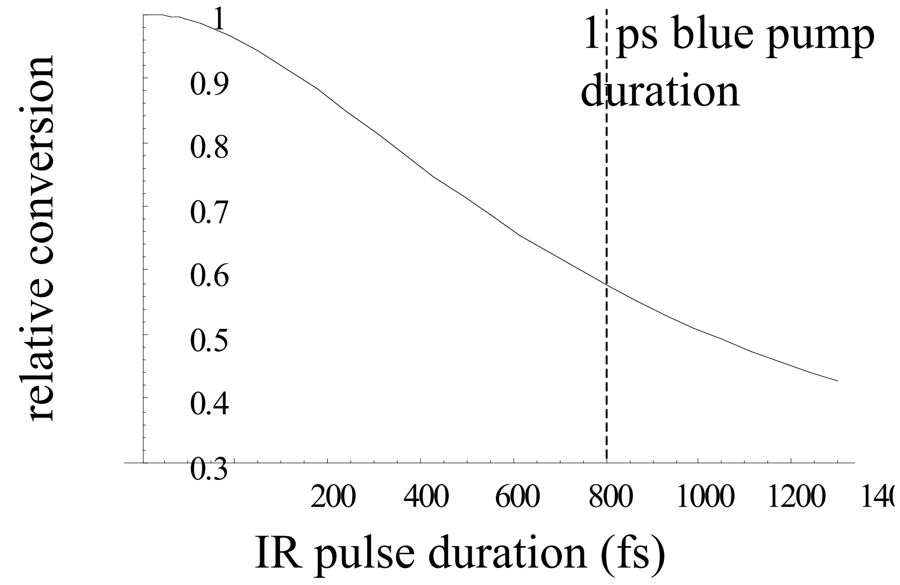


- dispersion compensation: short pulse IR into BBO and into capillary
- additional dispersion to blue
- control duration of IR w/add’l material

# Energy extraction

**Without saturation, UV output should *decrease* with greater IR duration:**

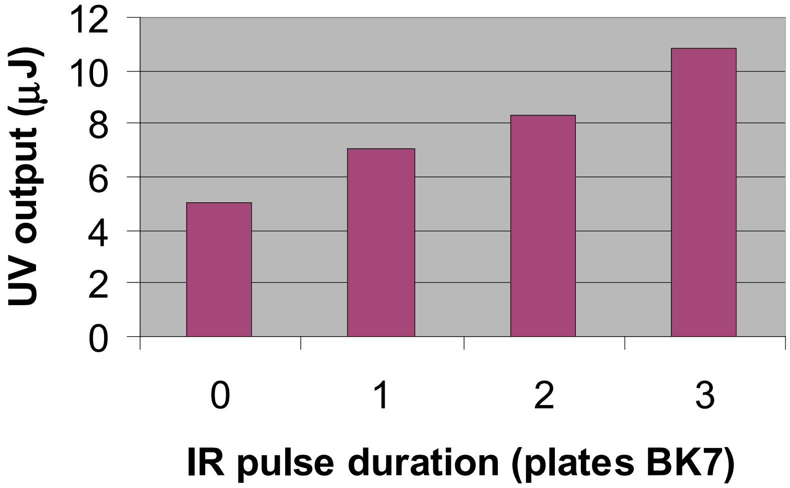
- signal is linear in IR



**With saturation, UV yield increases with IR duration:**

- longer IR seed can sweep out more of pump pulse energy
- cross-phase modulation is greatly reduced

# Energy conversion: experimental results



**Input: blue 110 fs, 48µJ IR: 40µJ**

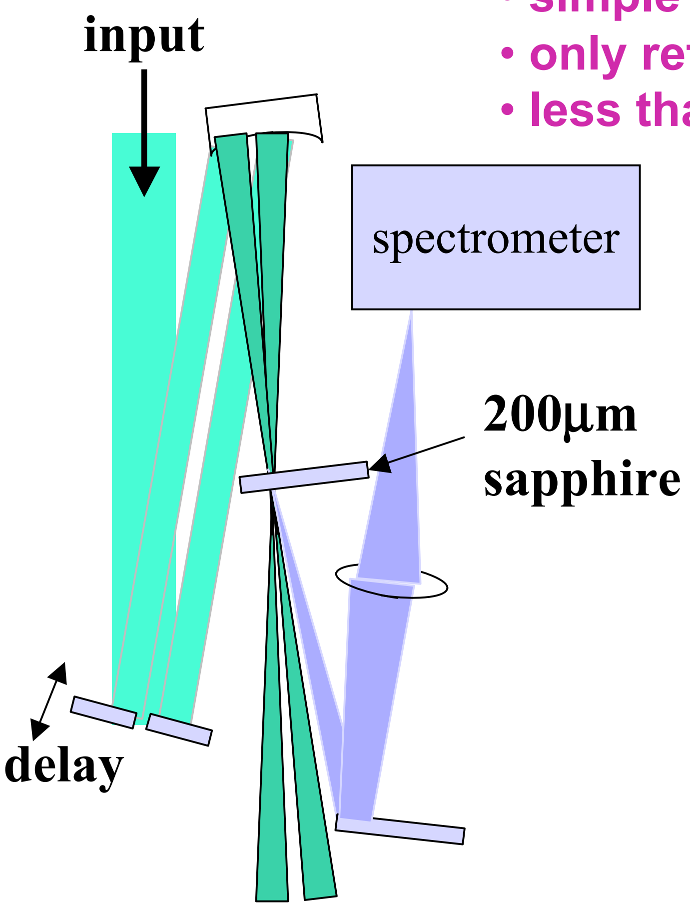
**Output *increases* with IR chirp:**

- **better overlap/extraction**
- **less XPM**
- **measure 20µJ depletion of blue (may not be seeing all of UV)**
- **limited by focusability of blue at high conversion**

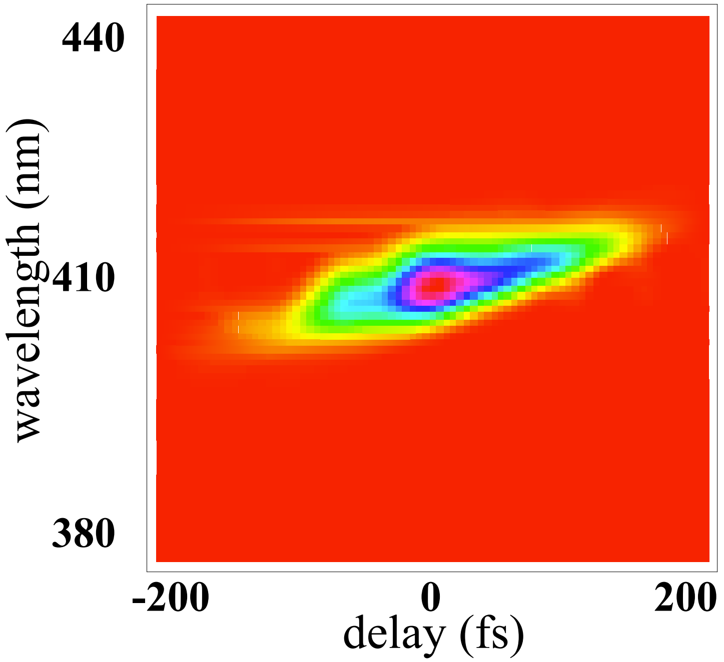
# Dispersion-free SD-FROG

## Three-mirror self-diffraction FROG:

- **simple setup/alignment**
- **only reflections: wide bandwidth/dispersion-free**
- **less than 1 μJ input required**



Durfee *et al,* Optics Letters **24**, 697 (1999)



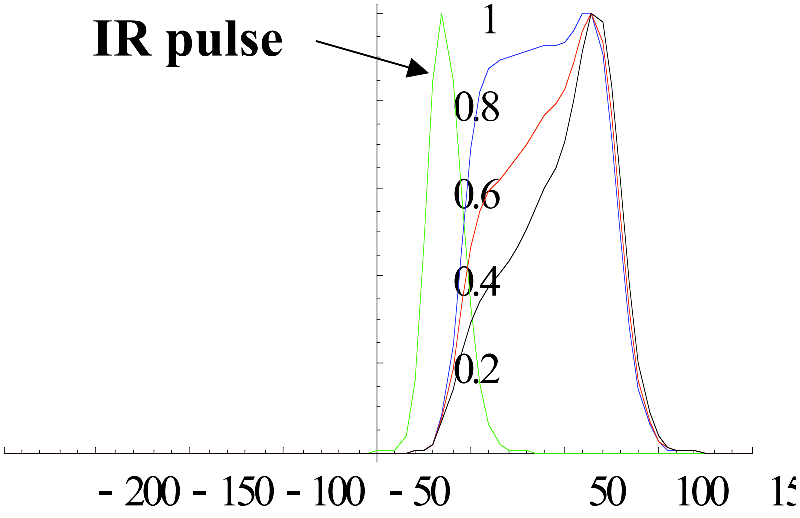
400nm pulse chirped w/6mm BK7

# High-power doubling

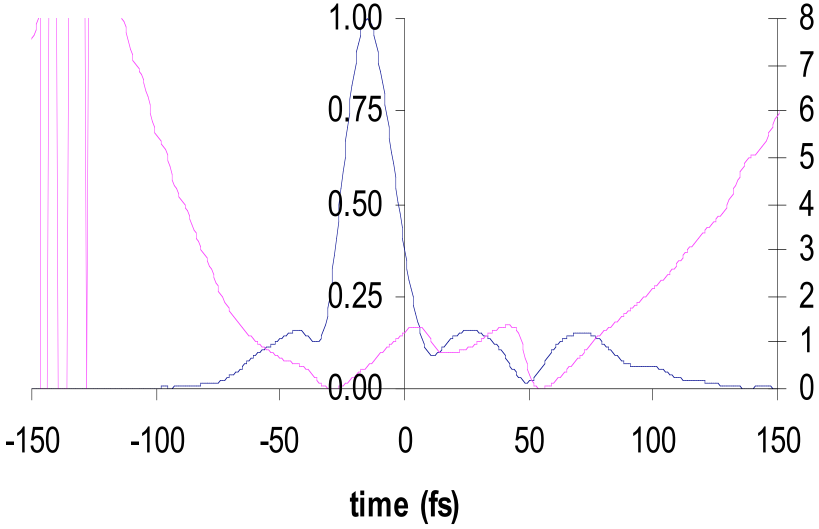
## Doubling at high conversion efficiency is easy...

- even with “thick” crystals, conversion gives short pulse
- conversion saturates in first layer of crystal

*calculation*



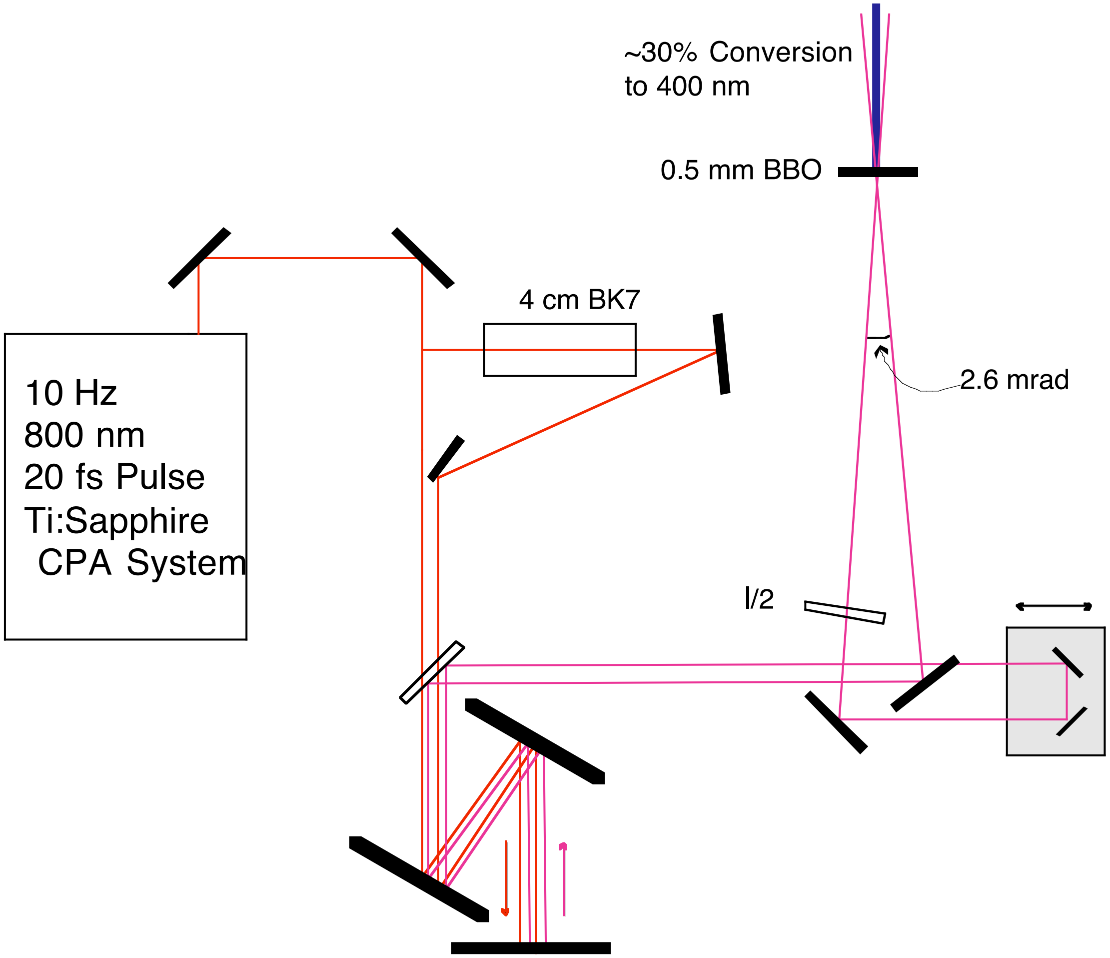
*measurement*



## … but preserving beam quality is not.

- At high conversion (~50%) focusing quality deteriorates

# Further scaling: opposite chirp mixing

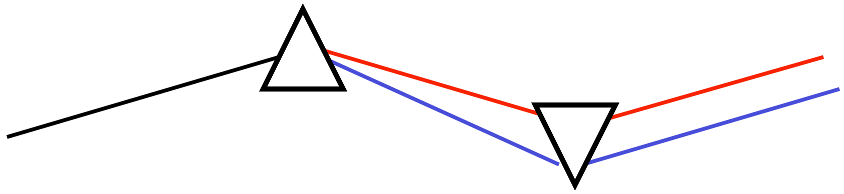


**Opposite-chirp mixing for blue → ~50% more output (14.5µJ)**

# OP-CPA: compression simulations

**UV output has negative chirp**

**(even orders of IR phase change sign)**

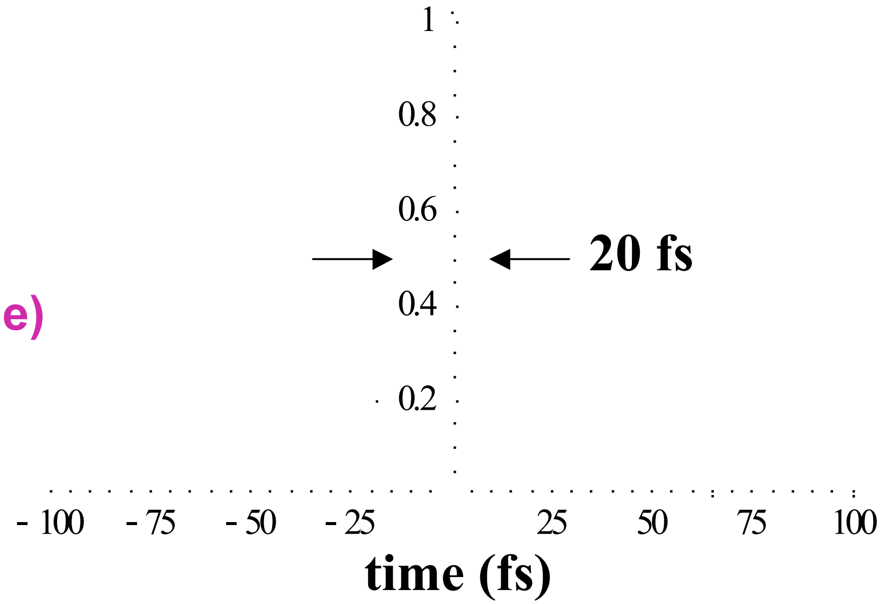


**Prism pair: +’ve dispersion mode**

**(correct sign of 2nd and 3rd order phase)**

**Compressed UV output as short as original IR pulse**

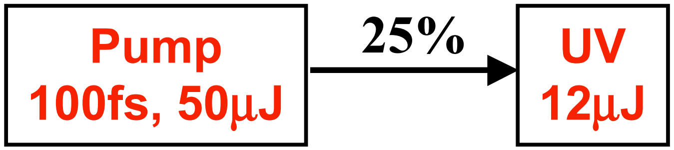
**(chirped pump gives shorter output)**



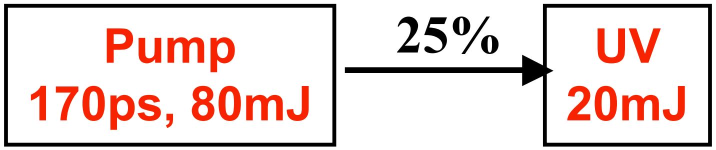
# Future prospects: energy/wavelength scaling

## Scaling to higher energy:

- higher-energy amplifier
- improve focusability of blue
- current:



- scale to TW level:



## Scaling to short wavelength for high-power VUV:

- pump pulse can be narrow-band
- mix 800nm with: YAG harmonics:
- 355nm → 230nm, 266nm → 160nm, 210nm → 120nm

# Applications of high-power UV pulses

- pump for recombination XRL
- tunneling ionization in high-frequency limit
- micromachining - materials processing
- hard x-ray generation
- efficient low-order HHG
- photoelectron spectroscopy: fast dynamics of small molecules

# Mixing simulations

## Propagation code calculates saturated conversion

Input fields:

•energy, pulse duration, chirp, relative delay

Pressure loop

Propagation step loop: split-step + Runge-Kutta

Time domain:

•spm, xpm

•nonlinear mixing

Frequency domain:

•dispersion, losses

Output processing:

•energy calculation

•post-compression

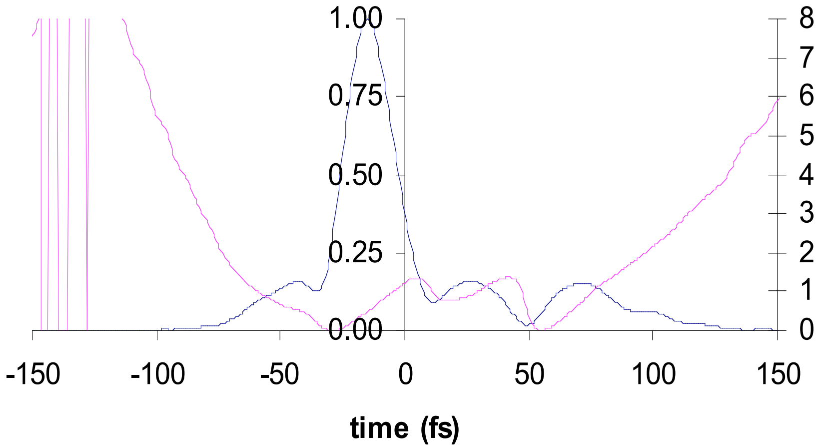
Major assumptions:

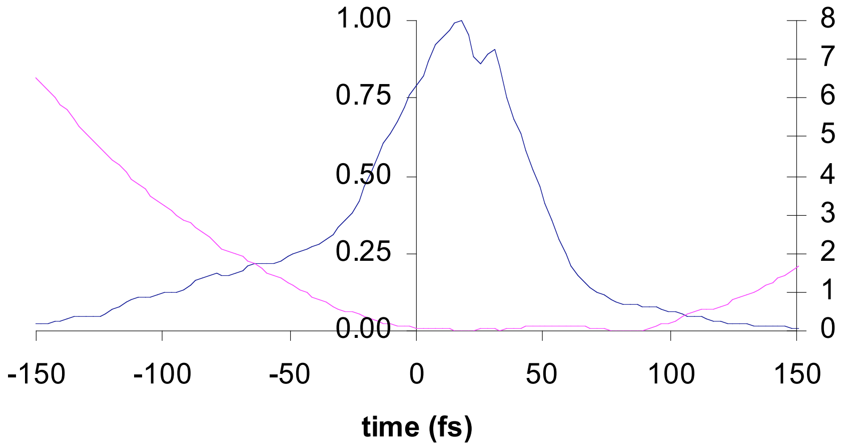
- *discrete-mode propagation*
- *five harmonic fields*
- *no bending losses*
- *no ionization*

# Characterization of input pulses

## Blue pulse:

- initially 35fs
- chirped to 110fs with 8.5mm BK7, 3mm fused silica





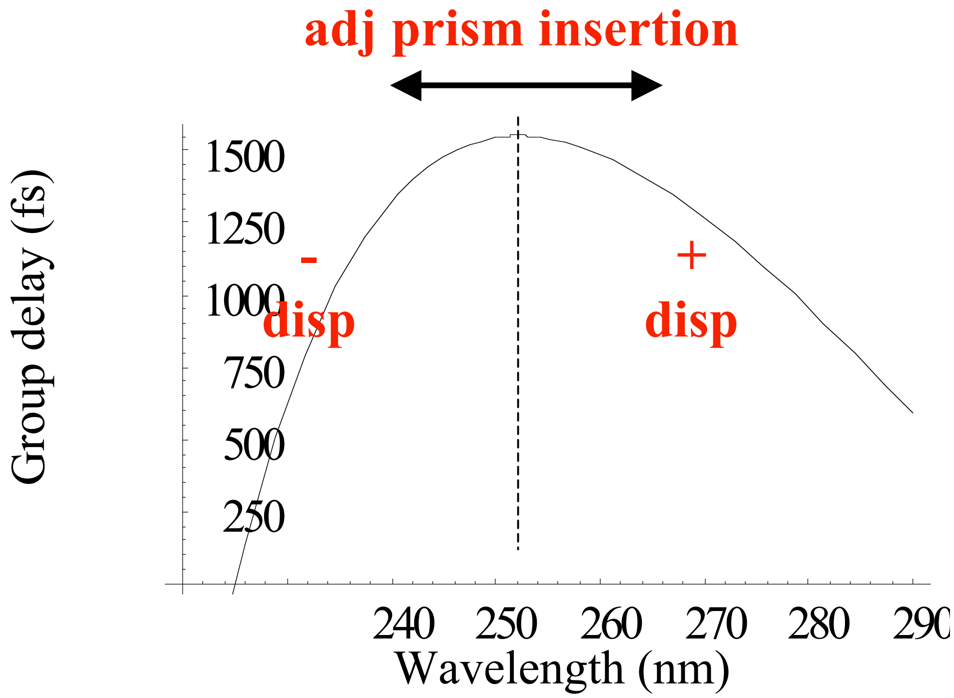
## IR pulse:

- initially 45 fs
- chirped to 51, 57, 63fs with additional BK7

# Compression

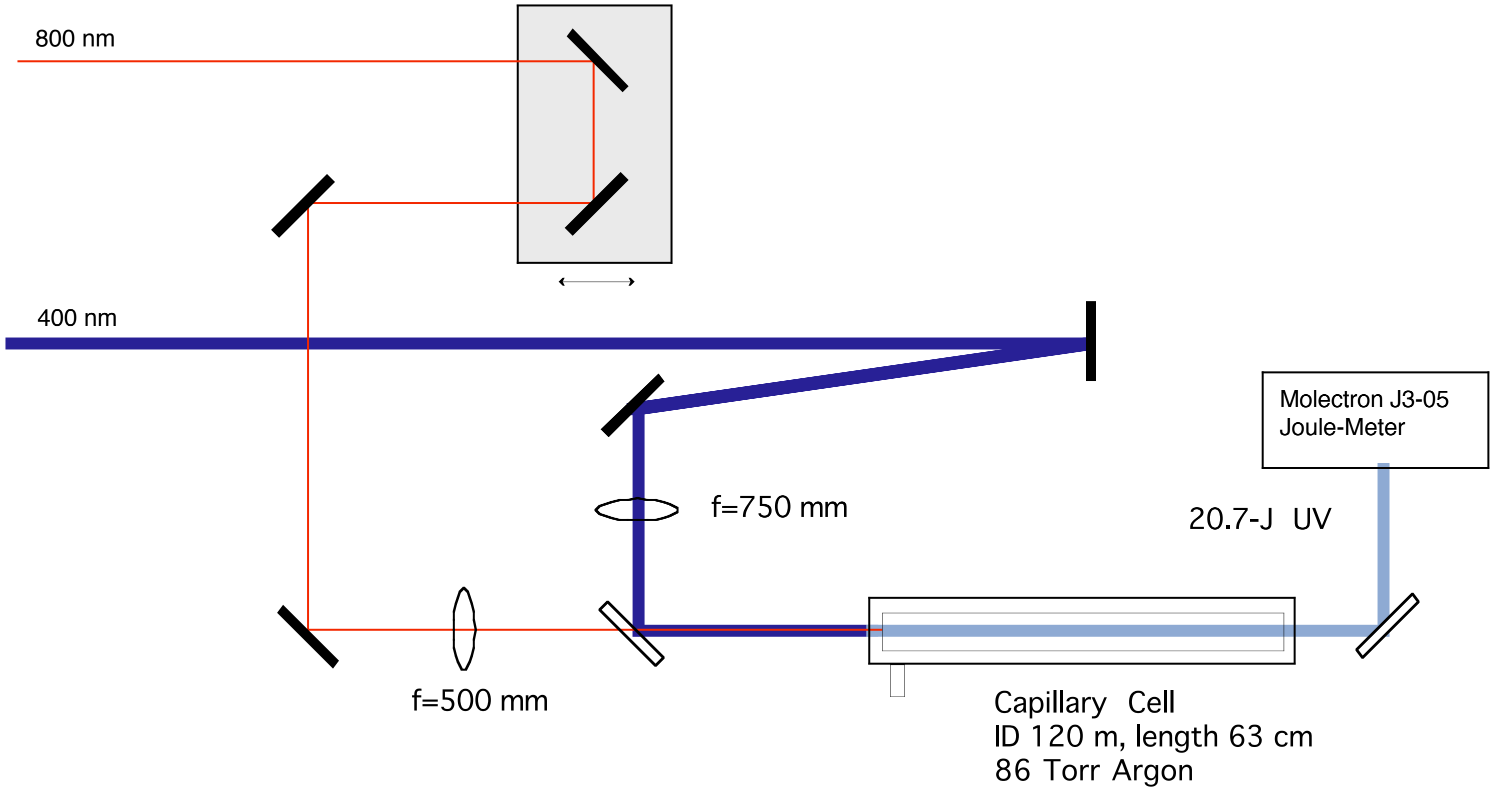
## UV pulse compression:

- positive IR chirp gives negative UV chirp
- simple compression with material not sufficient: 3rd order
- even orders of phase change sign, odd remain same



Group delay for FS prism pair (10cm sep)

- prisms in positive dispersion allow 2nd and 3rd order compensation
- characterize with SD FROG


800 nm
400 nm
Molectron J3-05
Joule-Meter
f=750 mm
20.7-J UV
f=500 mm
Capillary Cell
ID 120 m, length 63 cm
86 Torr Argon