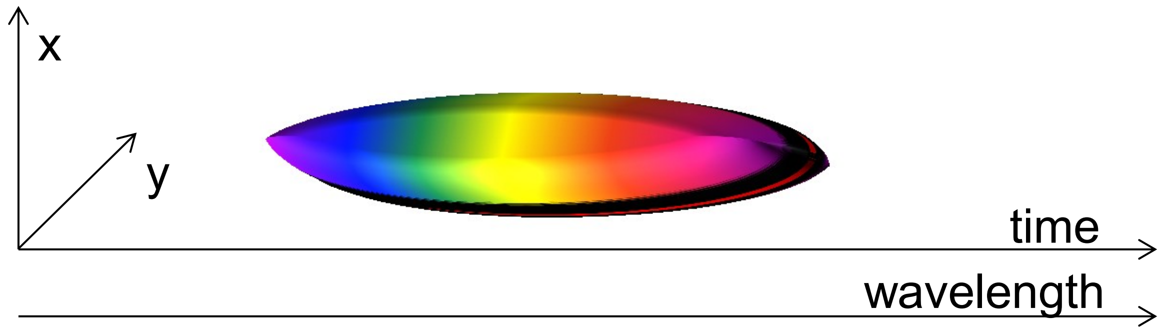
Pulse Shape Preservation in a Nonlinear Conversion Process

The ELLA2 Program



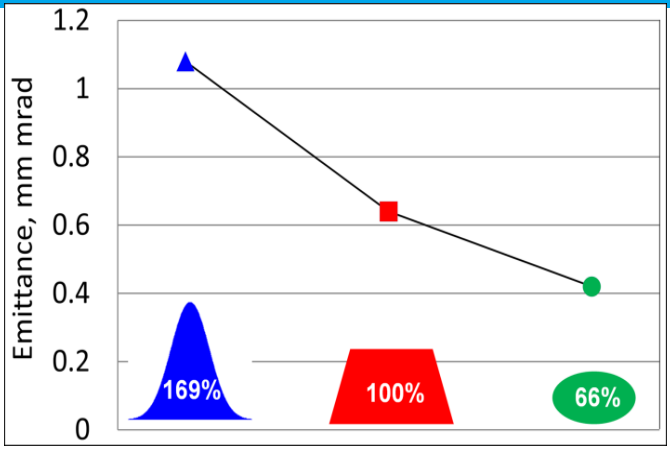
GOAL: Reducing electron beam emittance by 3D laser pulse shaping

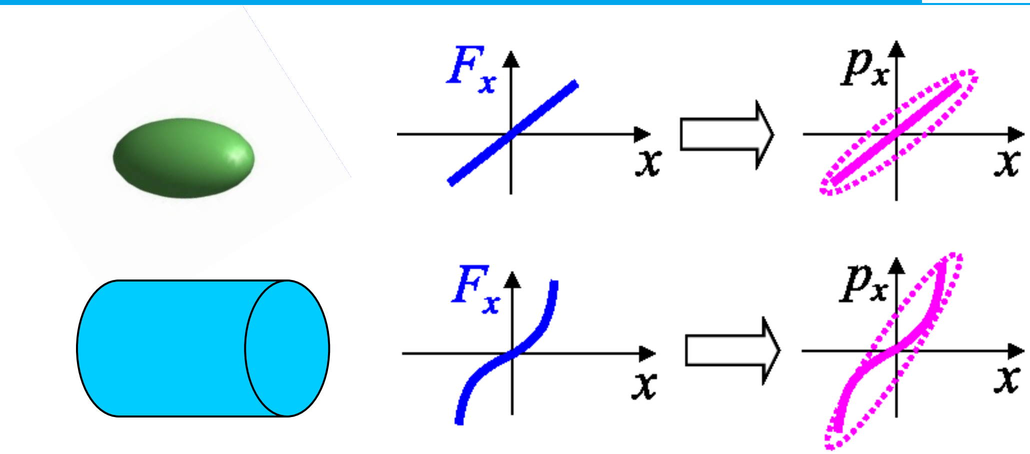
KEY: Temporal control via time-wavelength correlation in chirped laser pulses

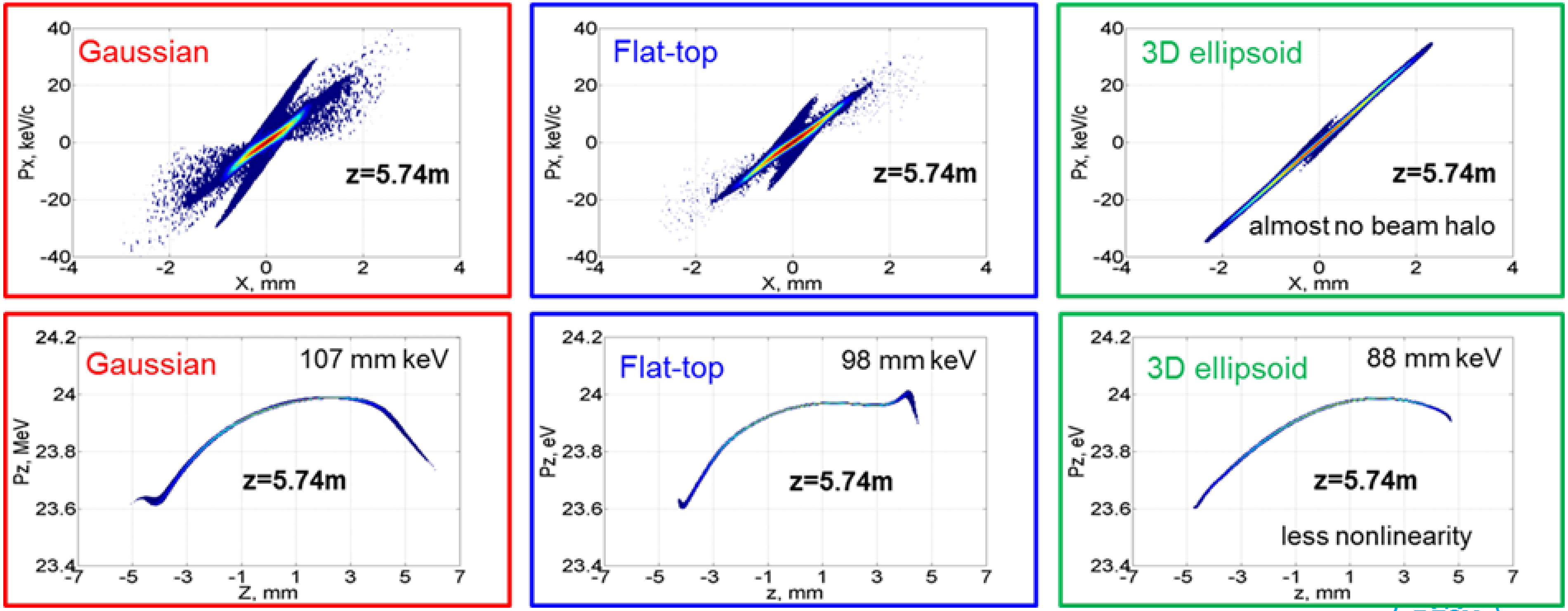
HELMHOLTZ ASSOCIATION

DESY

Beam overview for 3 different laser shapes (Zboo=3.1m)

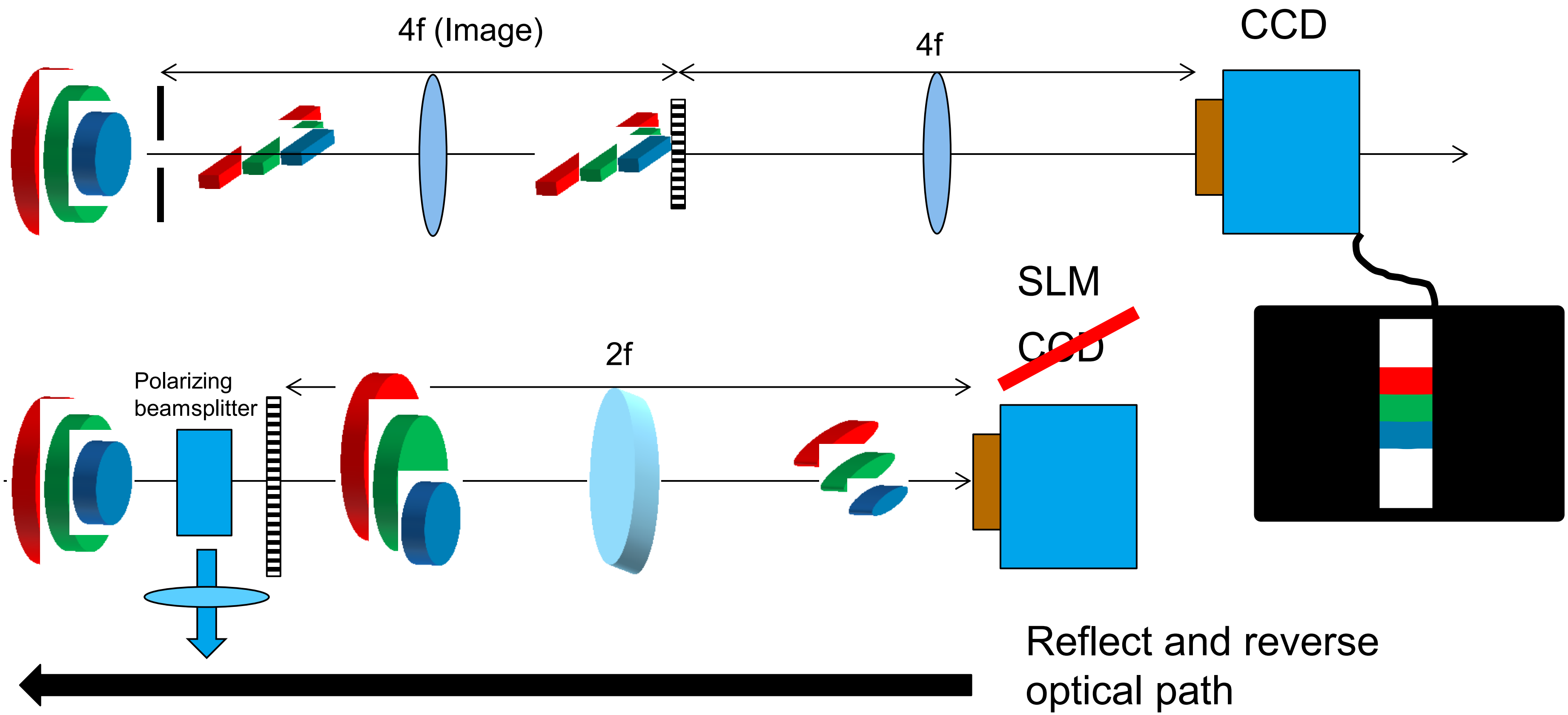


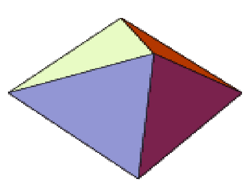




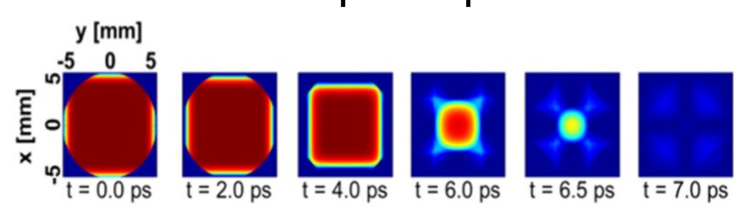
DESY

Example for the key principles: The spectrograph

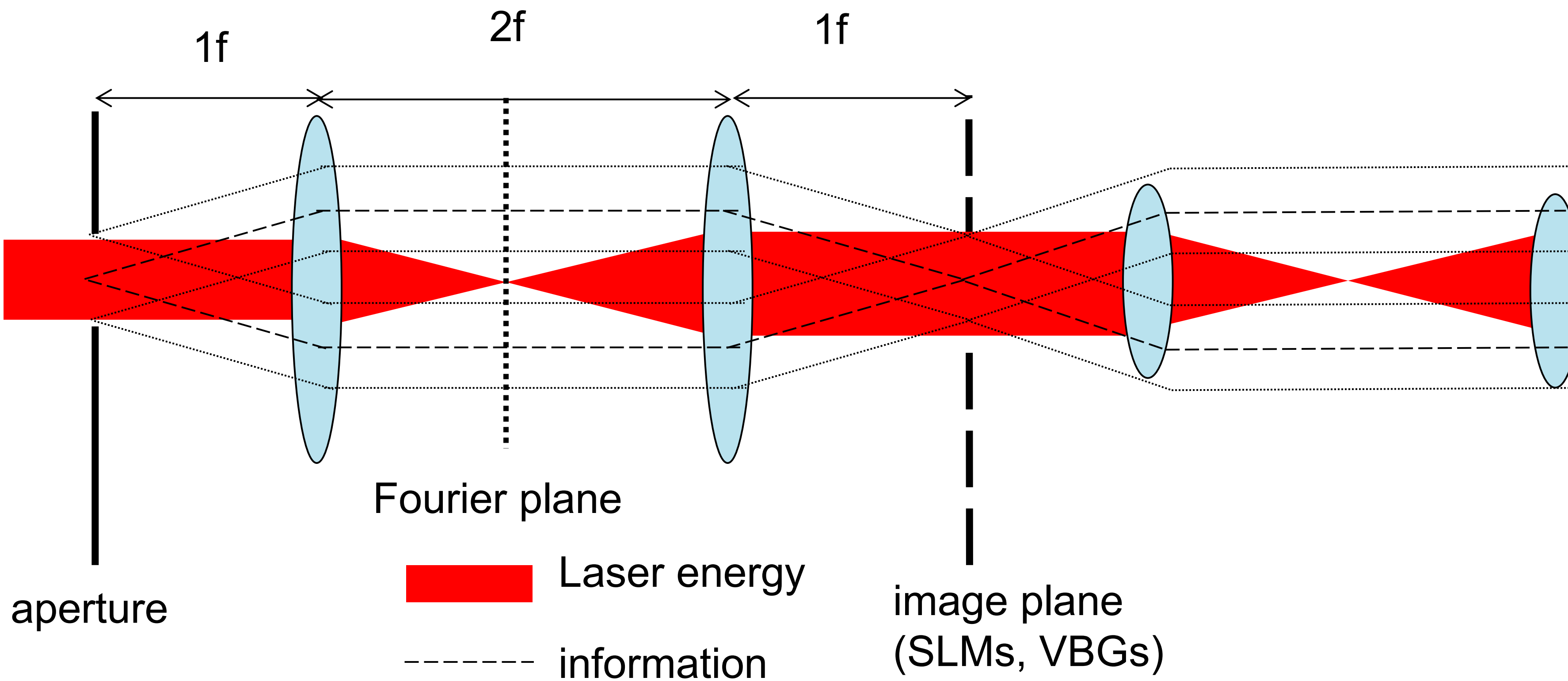




Only rectangular shapes
because of projection→
Dipyramid



Imaging throughout the system

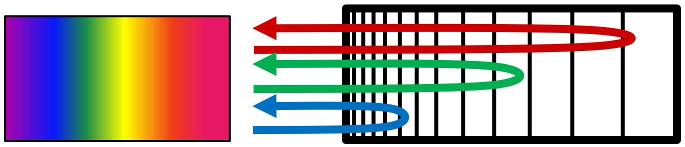


For every image image plane at x distance to a lens we need an additional distance 3*x

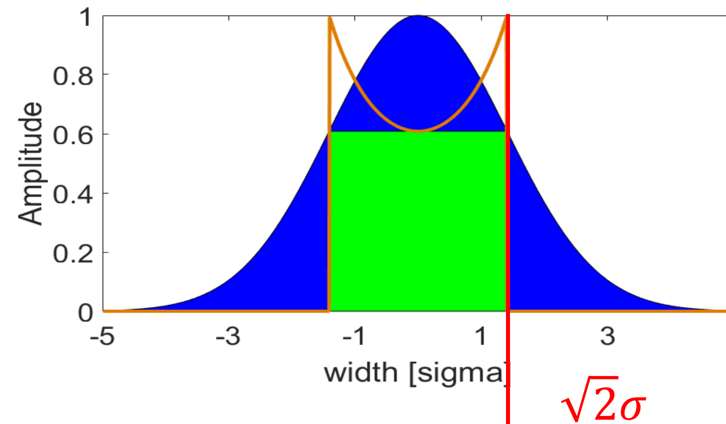
Cylindical lenses transport the image of only one plane (X or Y)

3D masking with Volume Bragg Grating

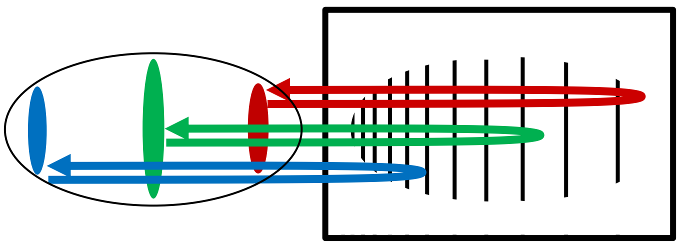
Volume Bragg Grating



BUT input has to be a flattop cylindrical shape



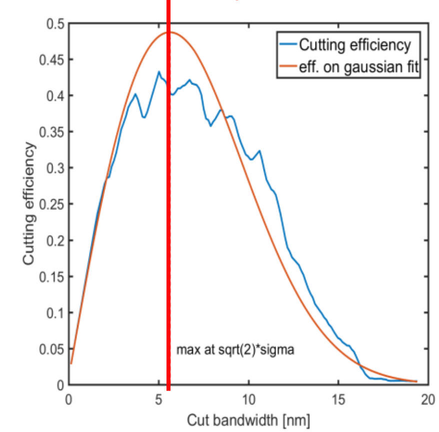
Modified VBG



Cut effiency 65 %

Cutting to Flattop from gaussian

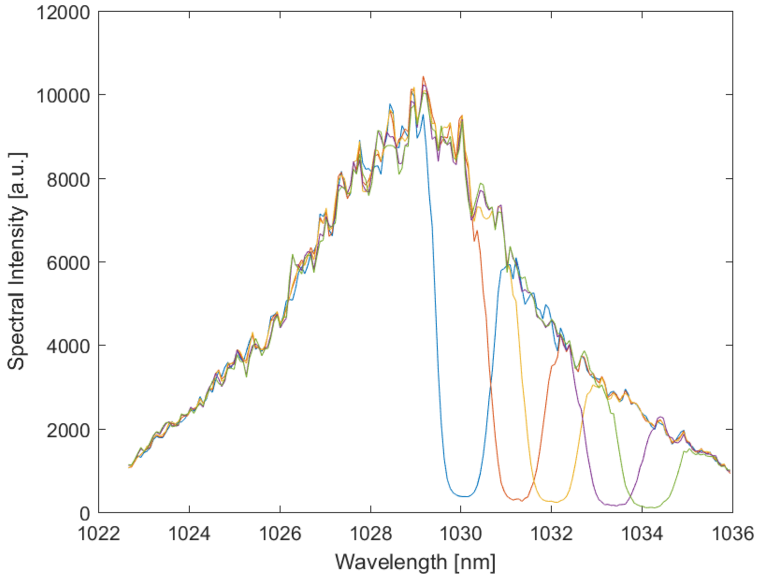
1D:	48 %
2D (circular):	36 %
3D (ellipse):	30 %

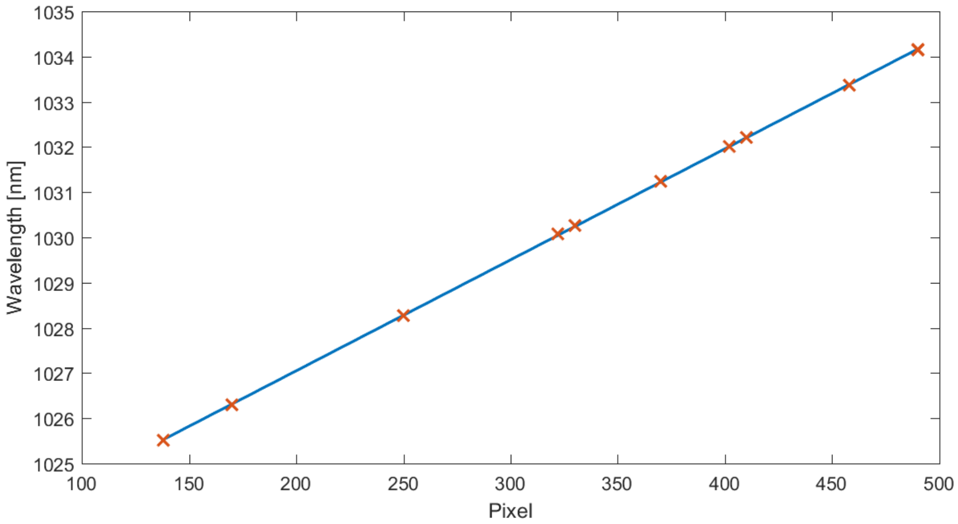


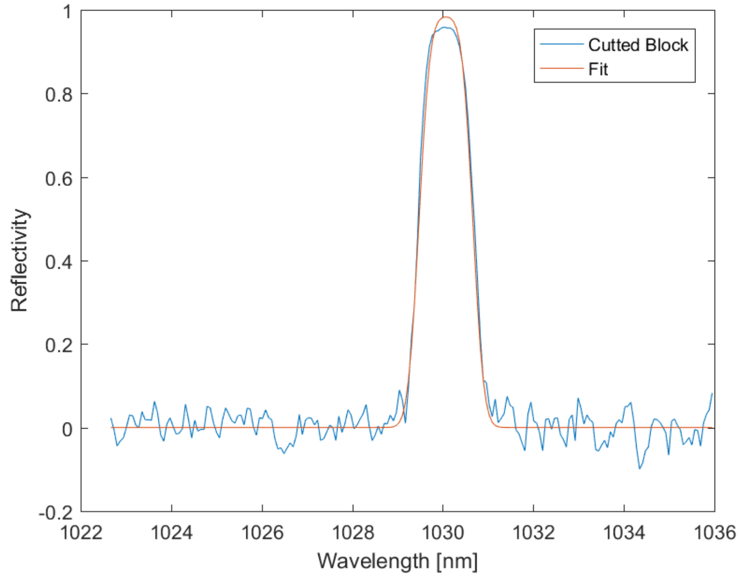
Spectral Mask (SLM + Grating) Eff: 48 % → Transverse Mask (SLM) Eff: 36 % → Modified VBG Eff: 65 %

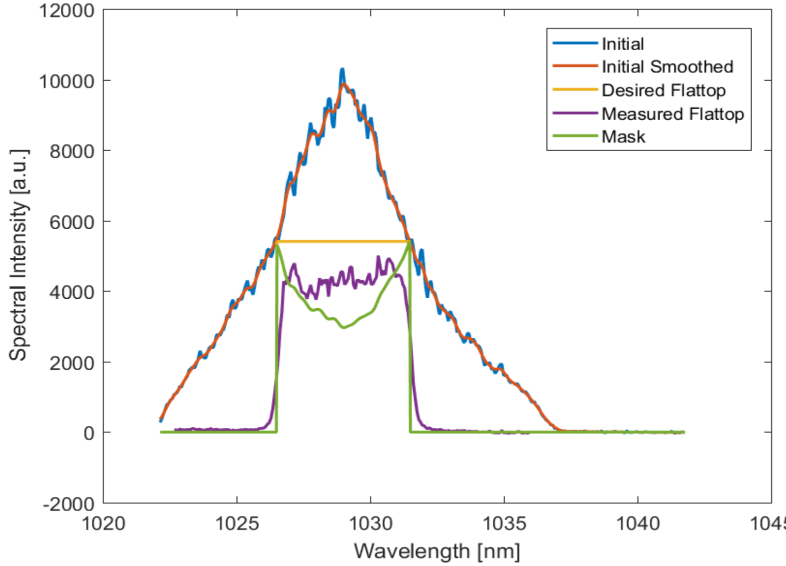
Maximum theoretical cutting efficiency: 11.5 %

Cutting a Flat Top in the spectrum



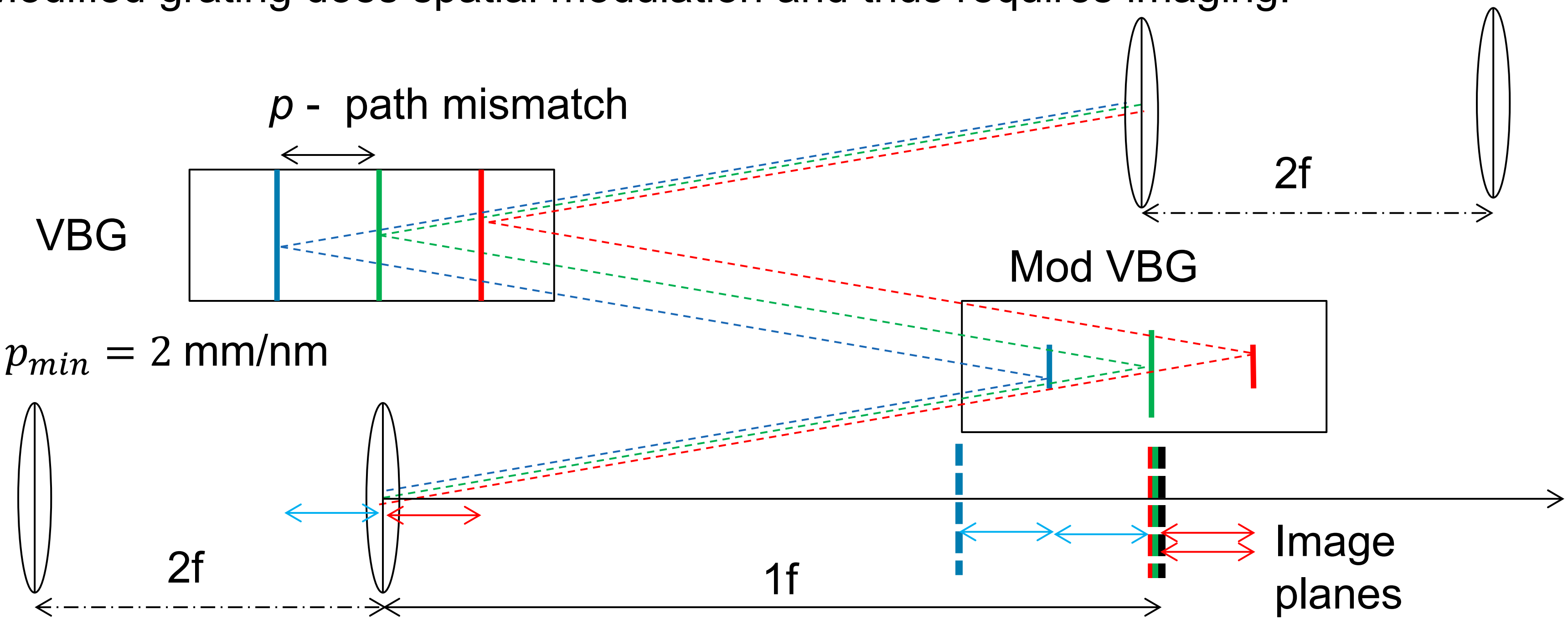






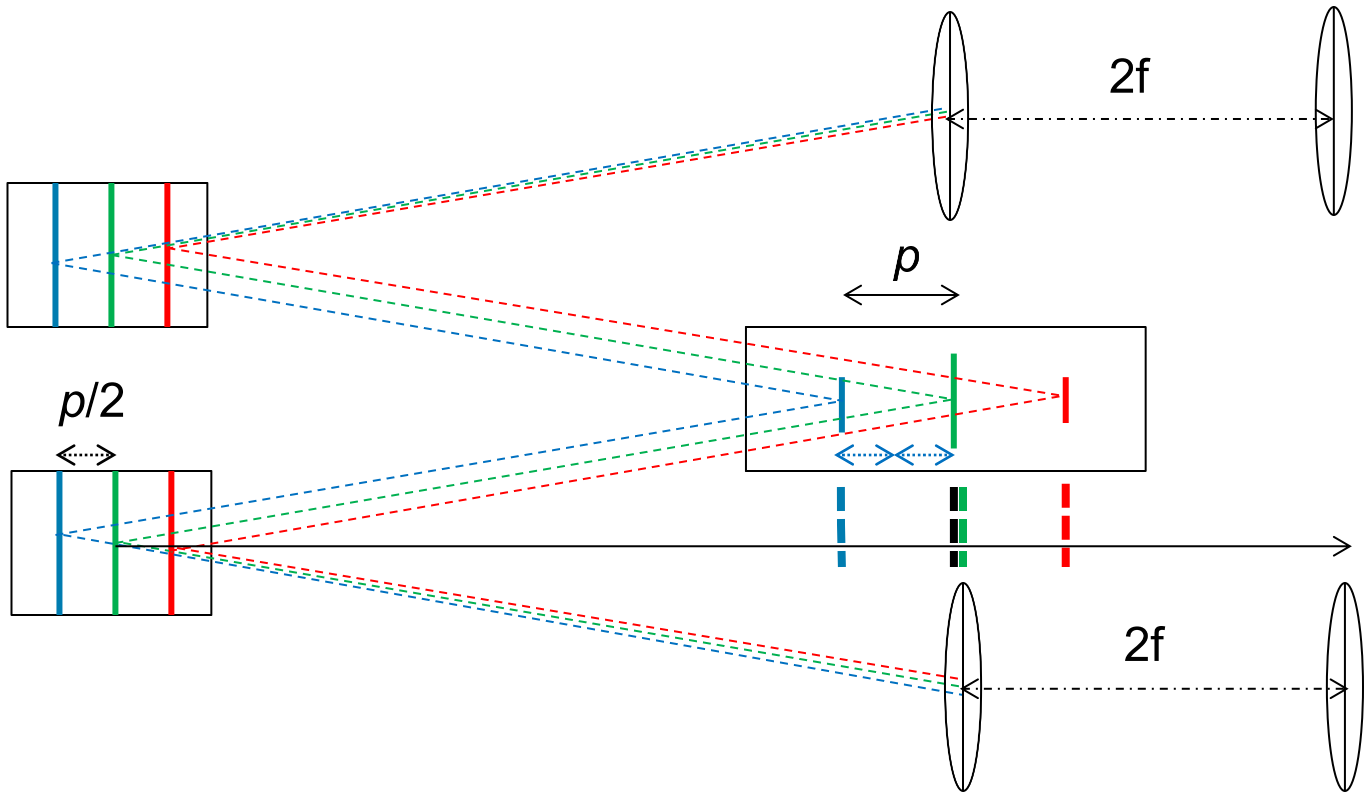
Imaging through the volume Bragg gratings

Modified grating does spatial modulation and thus requires imaging.



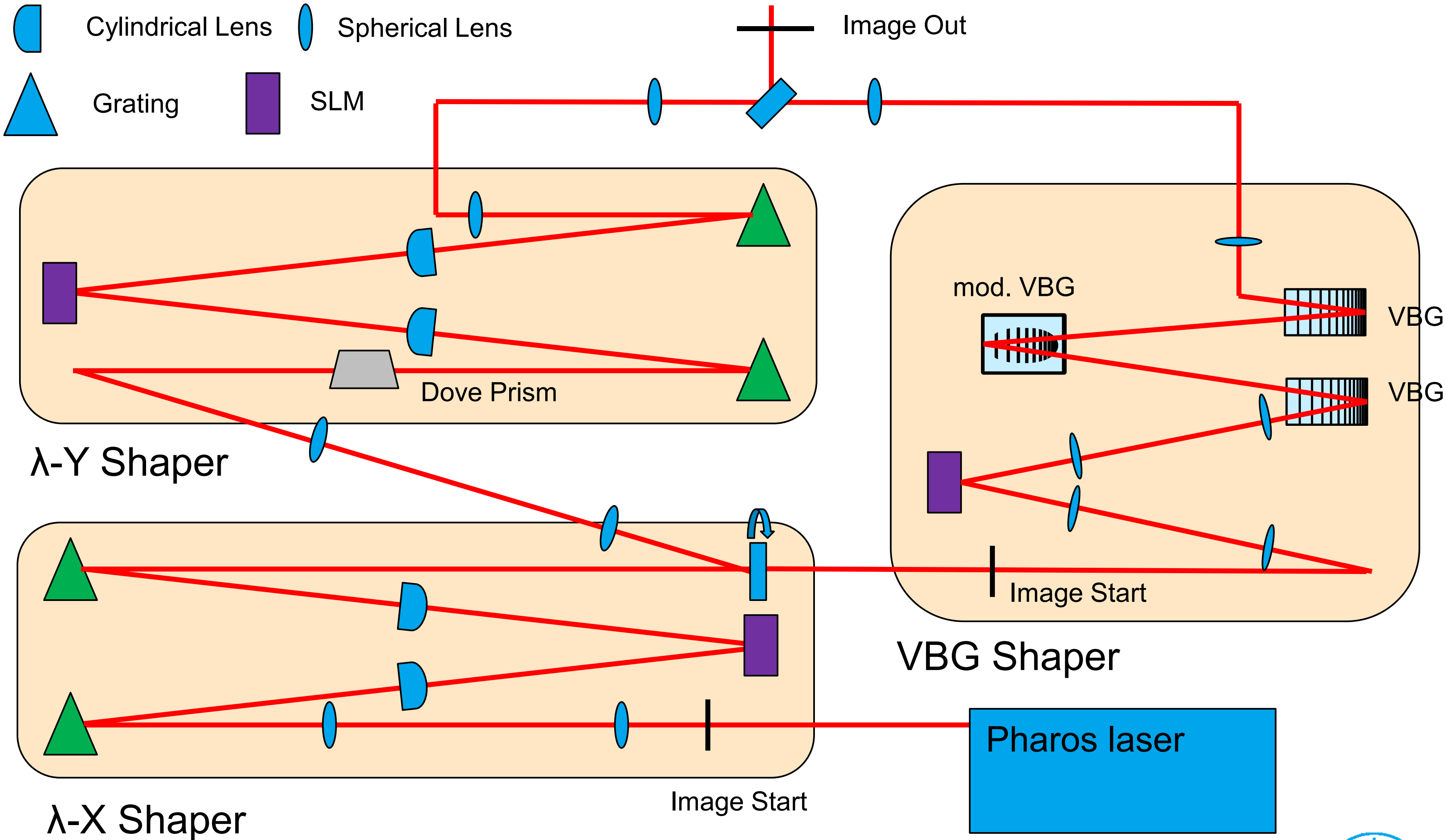
- Pulses are recompressed after dual VBG
- But the cutting inside the VBG is not done properly by p imaging mismatch
- Need to cut a sheered ellipse for angled setup

Imaging in a symmetric VBG compensation scheme



- Recompressed Beam
- Correct Imaging
- No sheered ellipse

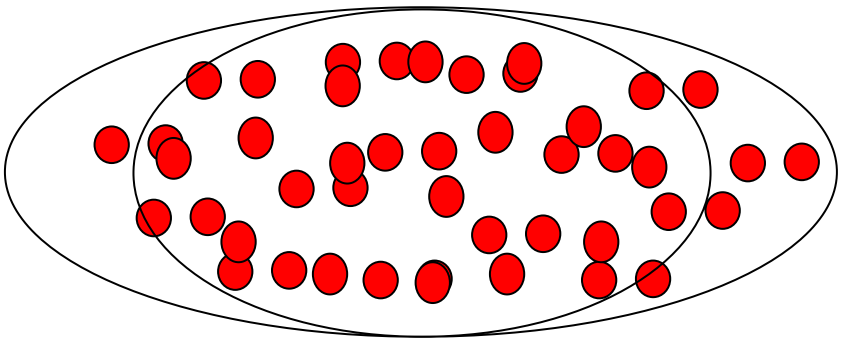
System layout



Conversion

Sum Frequency Generation (SHG): $\omega_1 + \omega_1 = \omega_2$

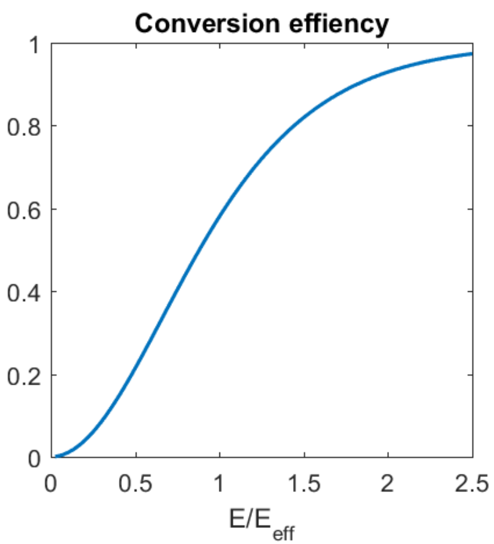
<u>Conversion rate is proportional to Intensity^2 and Volume</u>



A laser pulse with pulse energy *E* and duration τ converts 1% of the photons within a time *t* = 1mm/c

E doubles→ con. rate quadruples → efficiency doubles

τ halfs→ con. rate quadruples but Volume is half → efficiency doubles



$$\eta_{SHG} \sim \frac{E * L_{cr}}{\tau * {w_f}^2}$$

$$E_2 \sim \frac{E^2 * L_{cr}}{\tau * {w_f}^2}$$

Focusing limit

$$w_f = C\frac{\lambda}{N_A} \text{ with } N_A = \frac{D}{f} > 1$$

Pulse energy limit

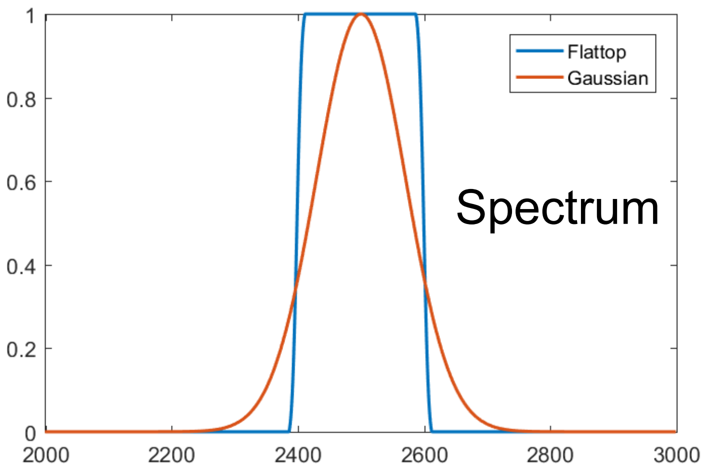
$$E * \mathrm{Rep} \leq 1\mathrm{kW}\ (20\mathrm{W})$$

$$E = 200\ \mu J\ (100\ kHz)$$

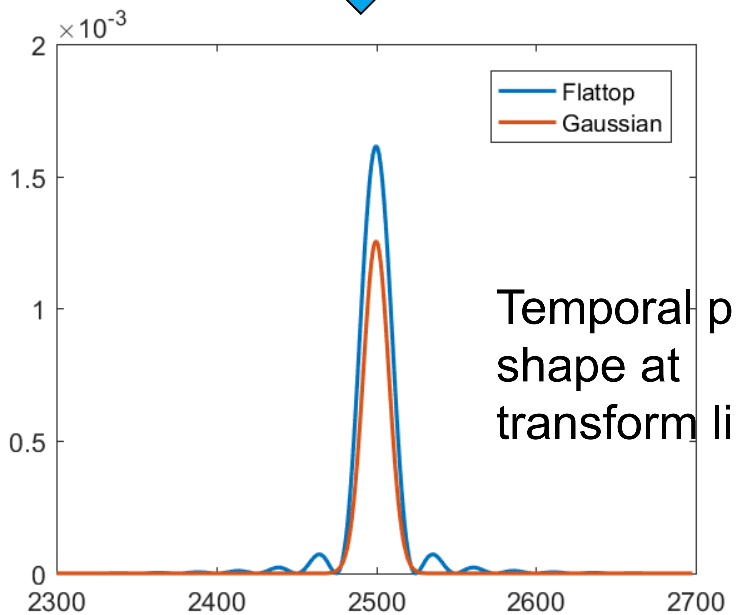
Pulse duration limit

$$\tau * \Delta\omega \leq 0.3$$

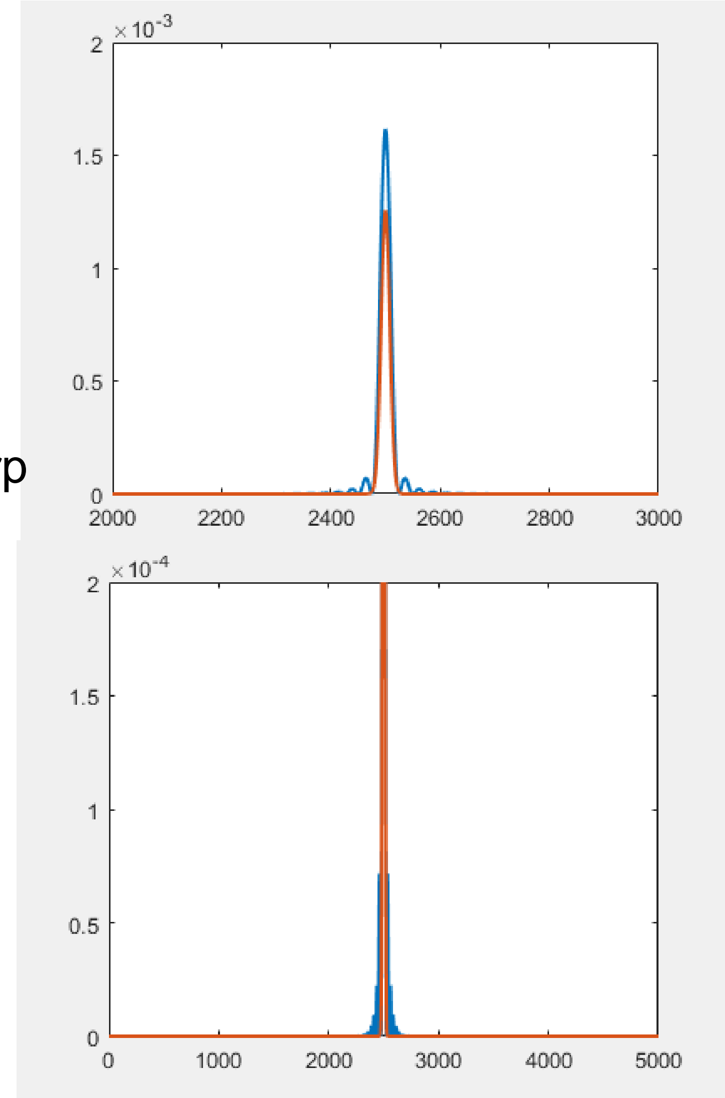
Fourier Transformation in Optics



F



Increasing chirp in two magnifications



Gaussian shape stability under transformation

$$f_g(x) = Ae^{-\frac{(x_0 - x)^2}{2\sigma_g{}^2}}$$

Squared

$$(f_g(x))^2 = f_g(x) \text{ with } \sigma = \frac{\sigma_g}{2}$$

Fourier Transf.

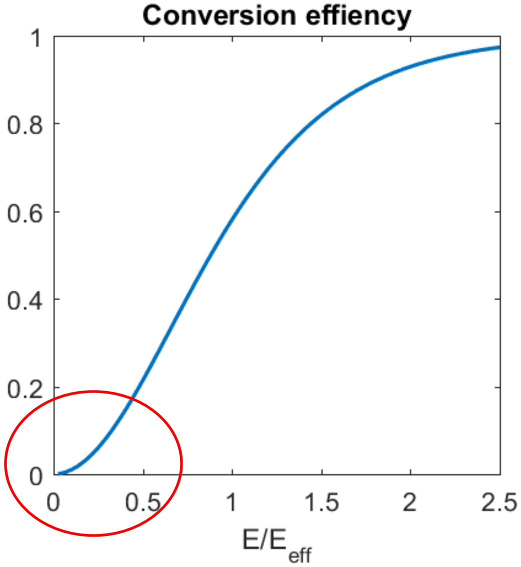
$$FT(f_g(x)) = f_g(x) \text{ with } \sigma = \frac{1}{\sigma_g}$$

Frequency Conversion (FC) with compressed/focused beam in unsaturated regime and perfect phase matching: $FC \rightarrow IFT(FT(f(x))^2)$

Frequency Conversion

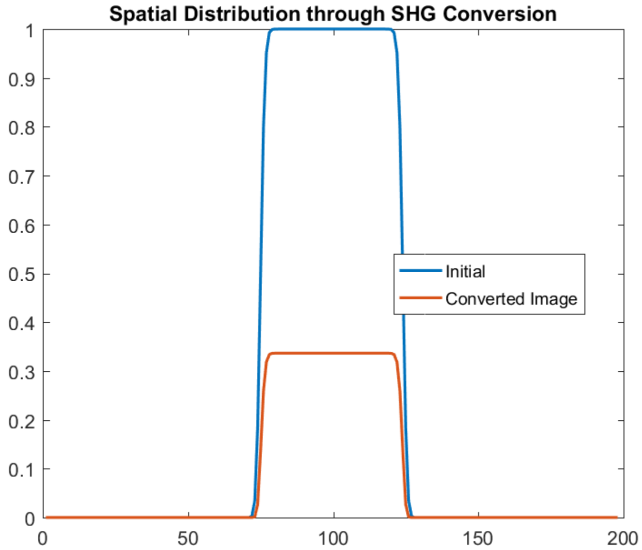
$$FC(f_g(x)) = f_g(x) \text{ with } \sigma = \frac{\sigma_g}{2}$$

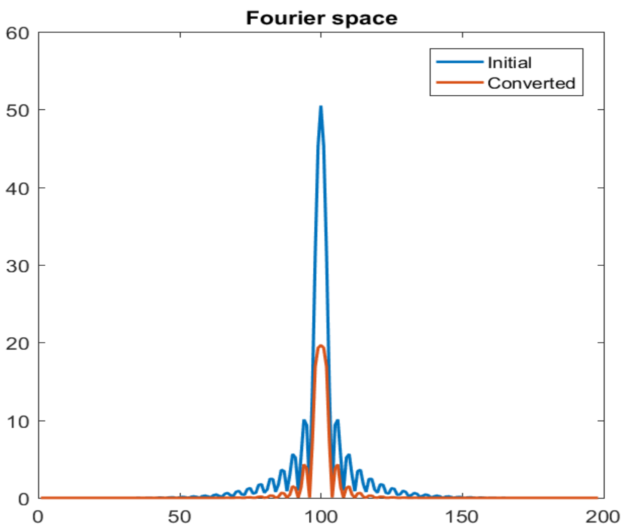
Flattop under FC transformation



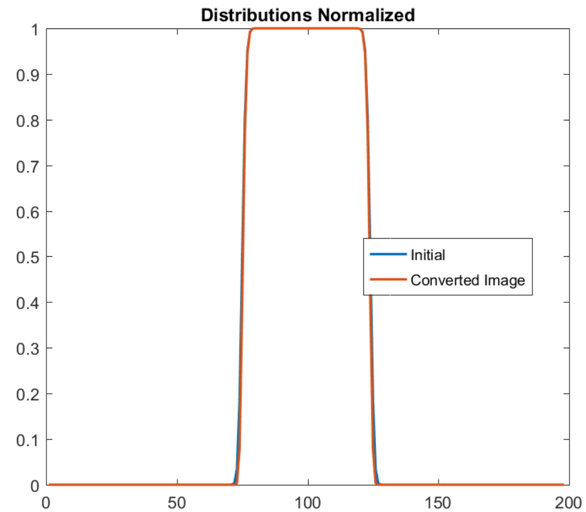
Conversion is proportional to Intensity^2.

Lowest part of distribution is always squared.

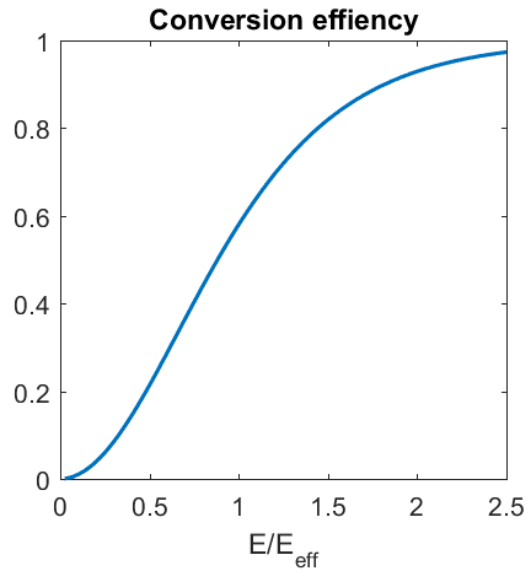




Conversion in Fourier Plane suppresses low amplitude high frequency parts.



Flattop under FC transformation



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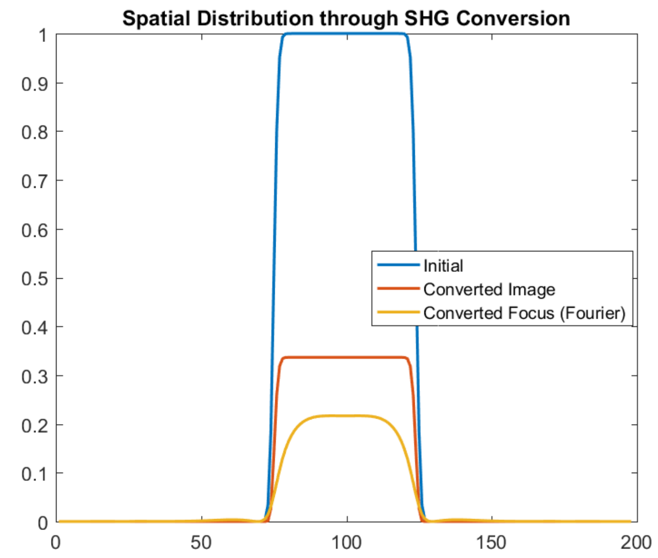

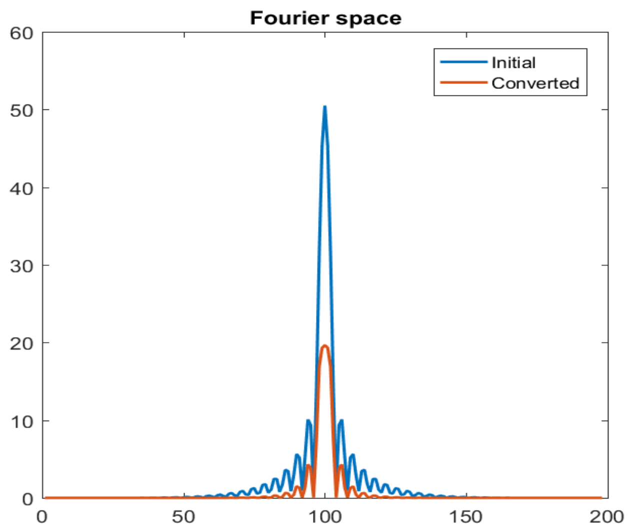

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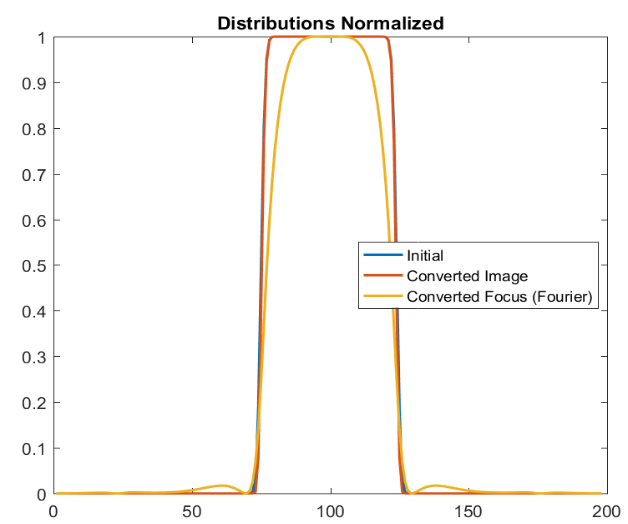
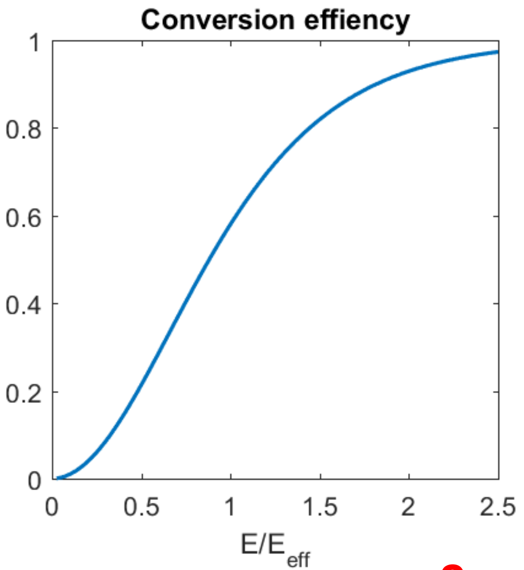


Flattop under FC transformation



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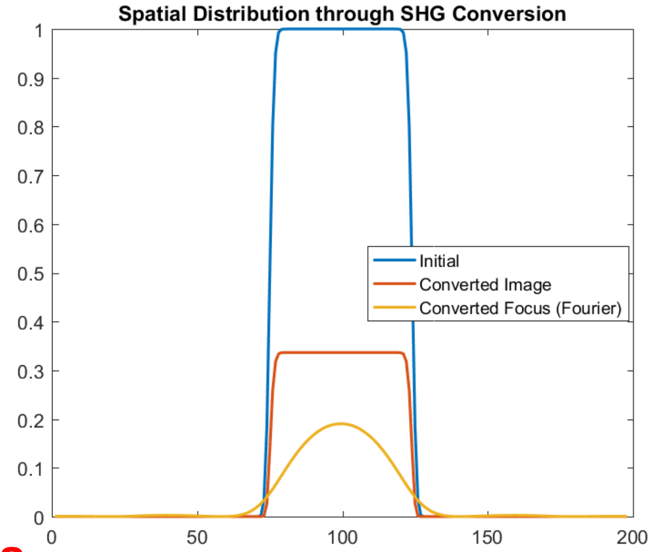
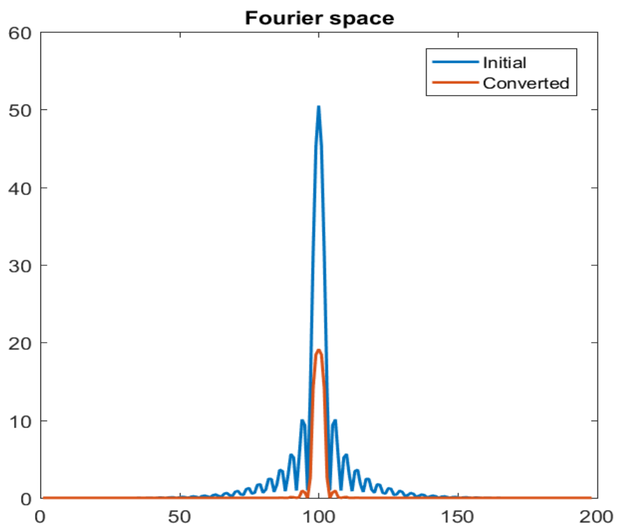


2 consecutive conversions



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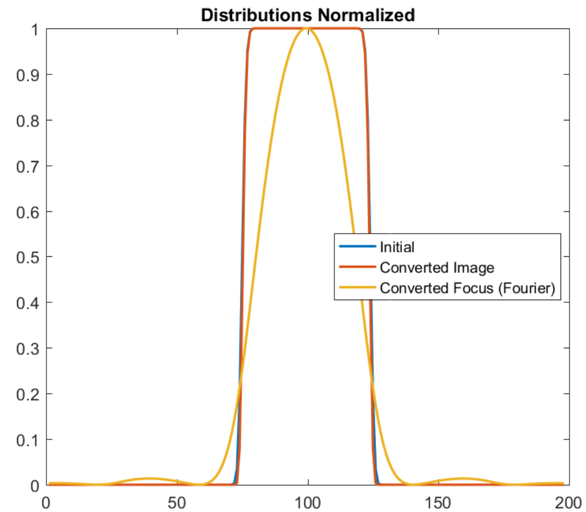
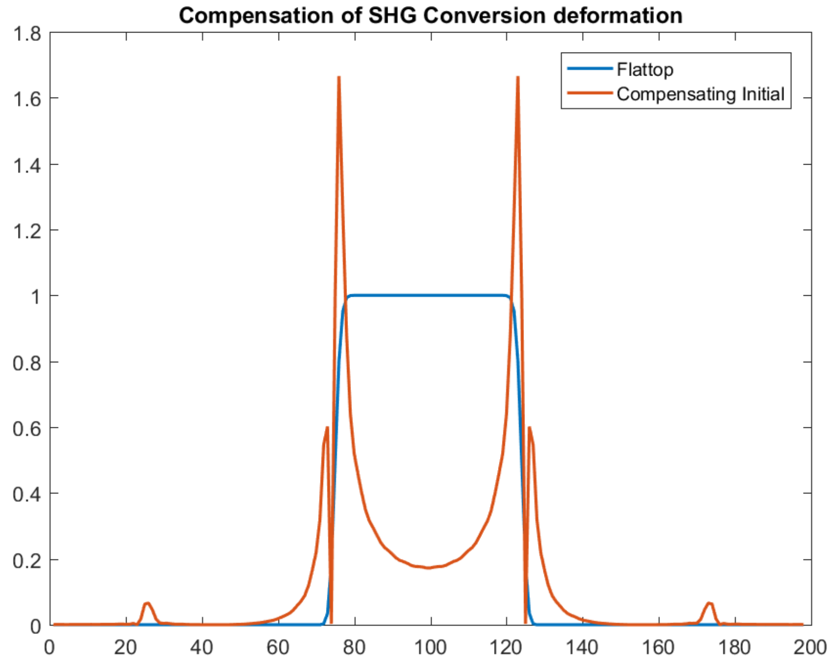


Compensating with predistortion



Has too low cutting efficiency!!

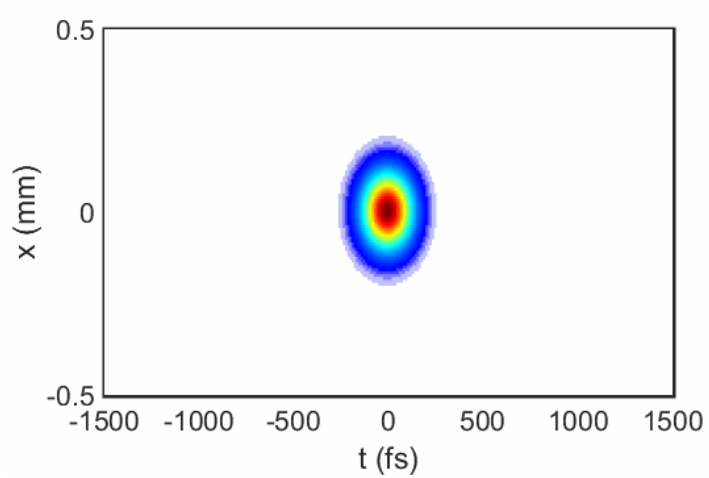
Shape preservation is a trade off
with energy efficiency!!!!

$$\eta_{SHG} \sim \frac{E * L_{cr}}{\tau * {w_f}^2} \qquad E_2 \sim \frac{E^2 * L_{cr}}{\tau * {w_f}^2}$$

Can we make crystal length long?

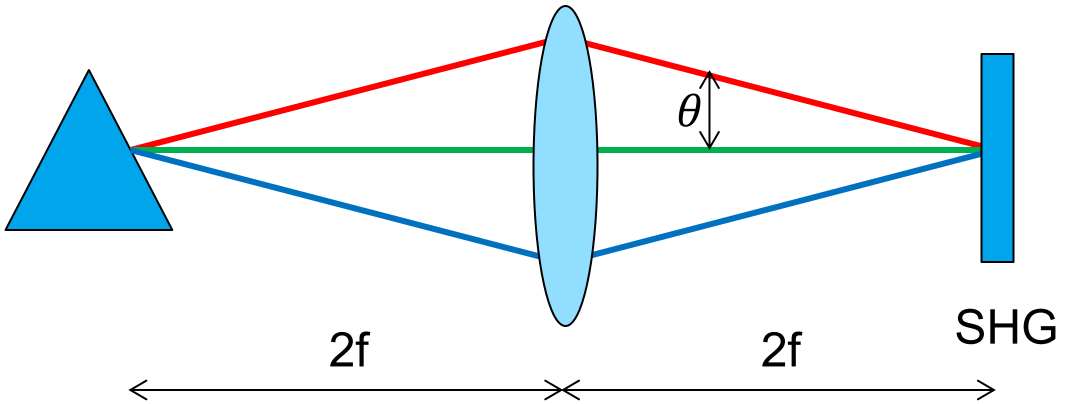
- Spatial Walkoff
- Group Velocity mismatch
- Low conversion bandwidth

NO



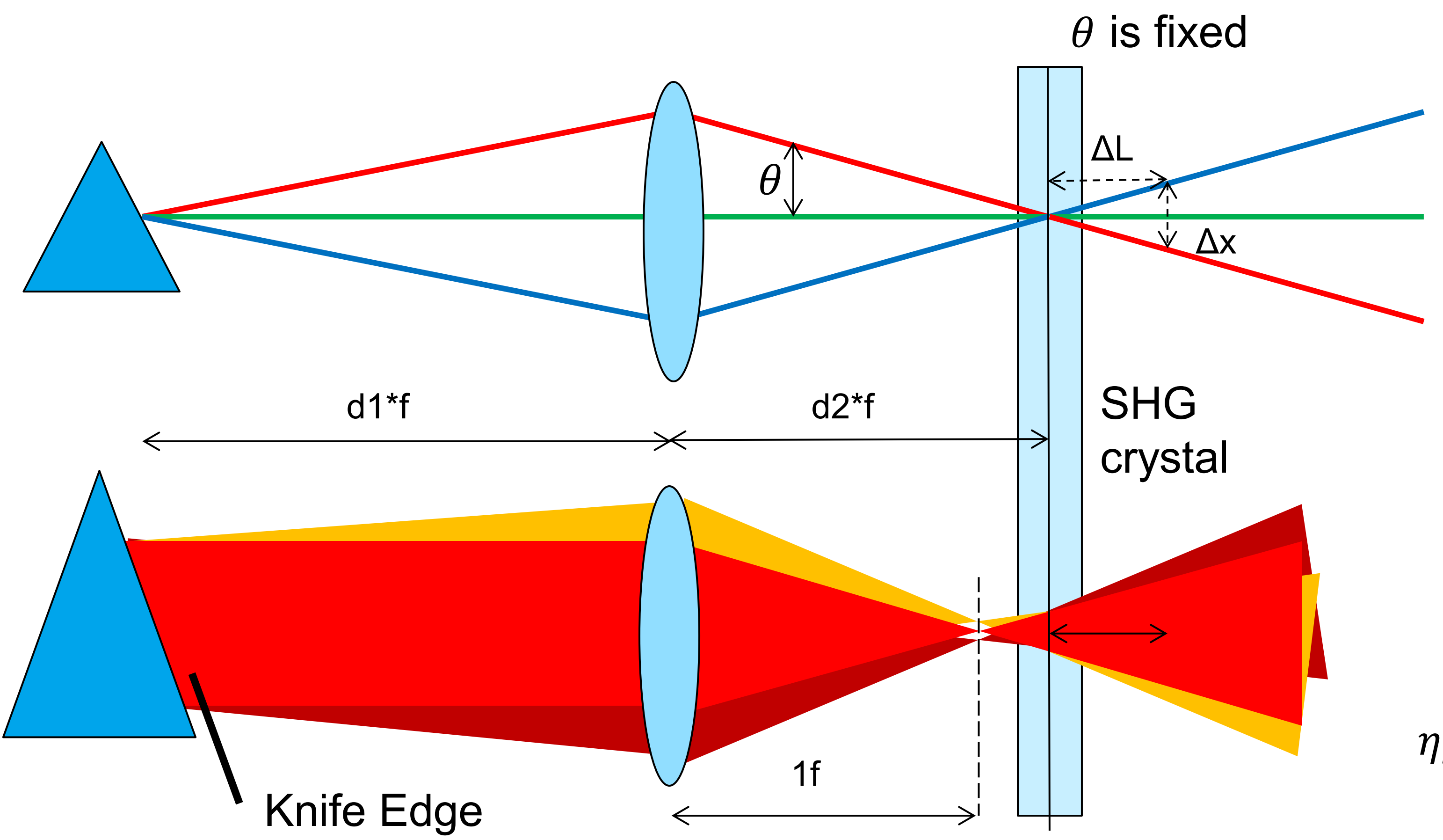
CHI2D simulation of SHG

Chirp and spatial flat top conversion (IAP RAS method)



θ is adjusted such that every wavelength gets tuned to the right phase matching

Solution for conversion bandwidth



$$\frac{1}{f} = \frac{1}{g} + \frac{1}{b}$$

$$M = \frac{b}{g}$$

$$\Delta x = \theta * \frac{L}{2}$$

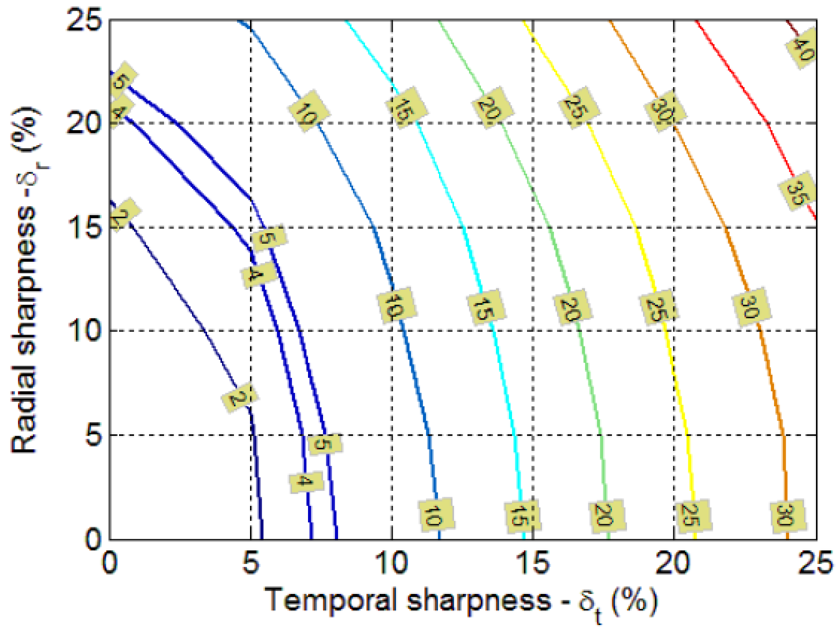
$$\frac{\Delta x}{M} = \text{resolution}$$

$$\eta_{SHG} \sim \frac{E * L_{cr}}{\tau * {w_f}^2}$$

Trade off between resolution and conversion efficiency → find optimum d1,d2,L_{cr}
Ultimately for a given resolution and efficiency a minimum pulse energy may be required. Should start investigation as soon as possible?

Emittance growth due to non perfect border width

- Modified intensity distribution for each border width (temporal and radial) has been put into ASTRA simulations for electron beam tracking up to EMSY1
- Parameters responsible for bunch rms emission time (initial bunch length) and laser beam transverse projection onto the z axis were kept unchanged during the studies



Transverse emittance growth (in %) vs. temporal (δ_t) and radial (δ_r) border sharpness parameters.

Strong effect of imperfections in temporal direction on transverse emittance

10-15% overall imperfections in 3D laser shape are still acceptable

Conclusion

- We don't have the full recipe!!! No workhorse system for electron experiments in 2018.
- Chirp technique must also provide ellipsoidal pulses. Only temporal shaping is easier with pulse stacking.
- Maybe need additional amplifier stage with shape preservation
- Next Steps: Proof of principle for stable red ellipsoidal

  Investigation of Resolution / Conversion Eff. Trade Off
- Improve communication with collaborators.
- Is ≤ 30% (?) emittance improvement worth it?

Thank you for your attention