R&D experiments at BNL to address the associated issues in the Cascading HGHG scheme

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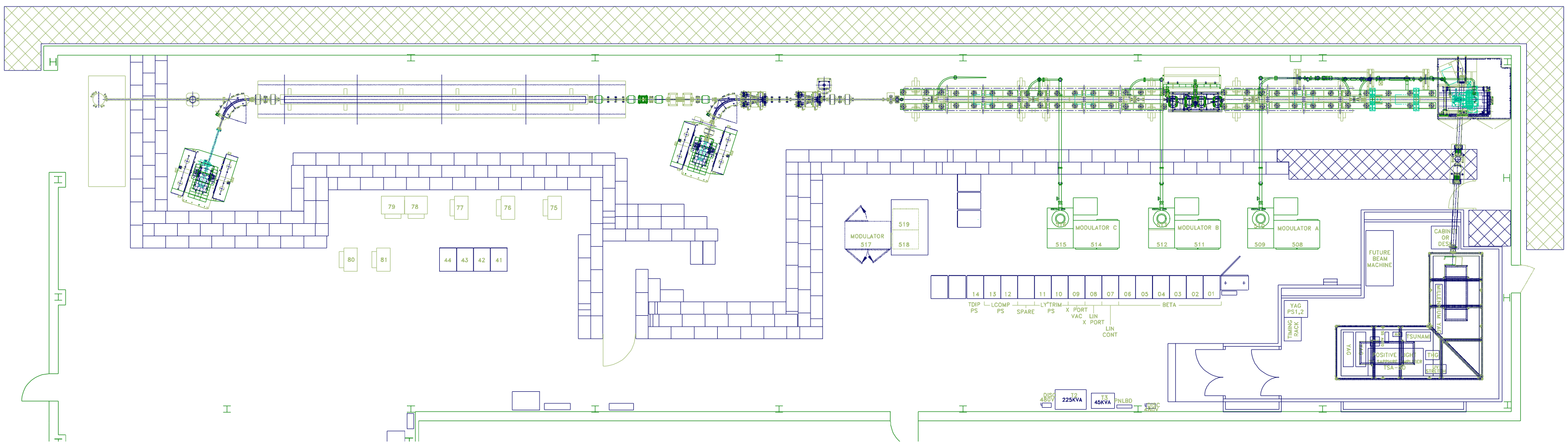
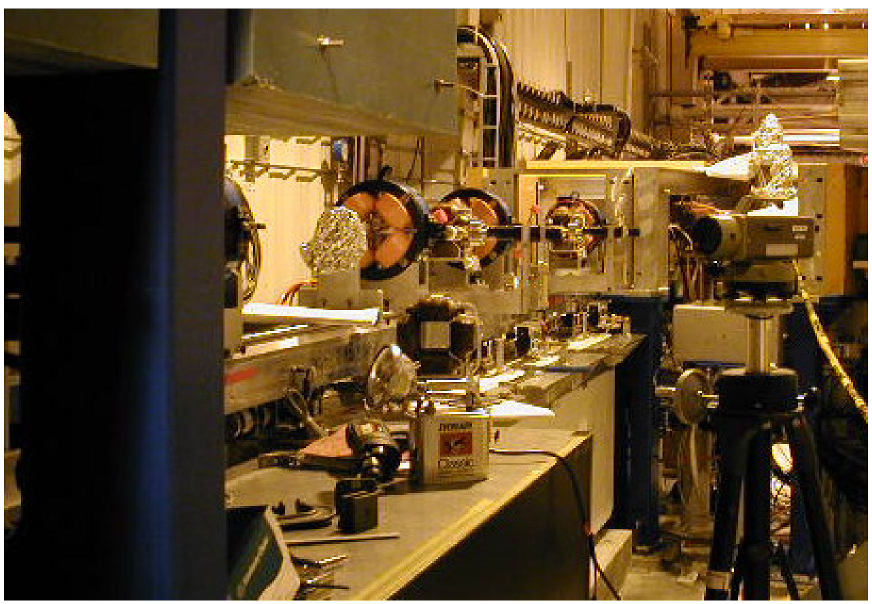
Outline

- The DUVFEL performance and the system parameters
- Suggestion on some of the experiments that can be carried out at DUVFEL to address the associated issues in the Cascading HGHG scheme

DUV-FEL Configuration





DUVFEL using NISUS wiggler

Step 1. SASE at 400 nm (2. 2002)

Step 2. direct seeding at 266nm (8.2002)

Step 3. HGHG 800nm → 266 nm(10.2002)

After energy upgrade

Next Goal 400nm → 100 nm

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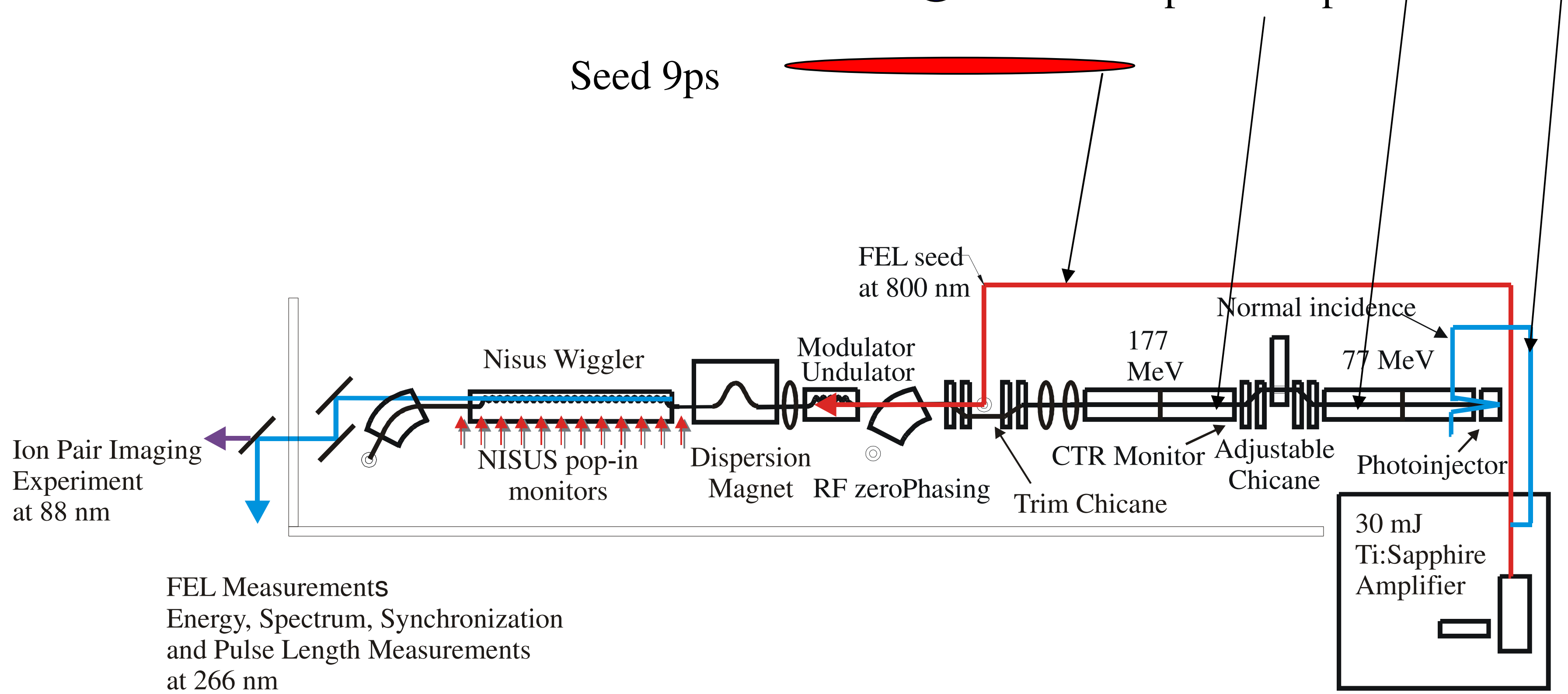
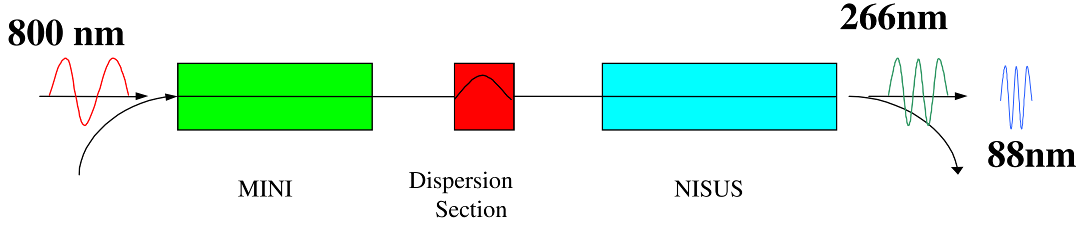
Deep UV Free Electron Laser at SDL

Relation of pulse lengths

During 2002-2003 operation



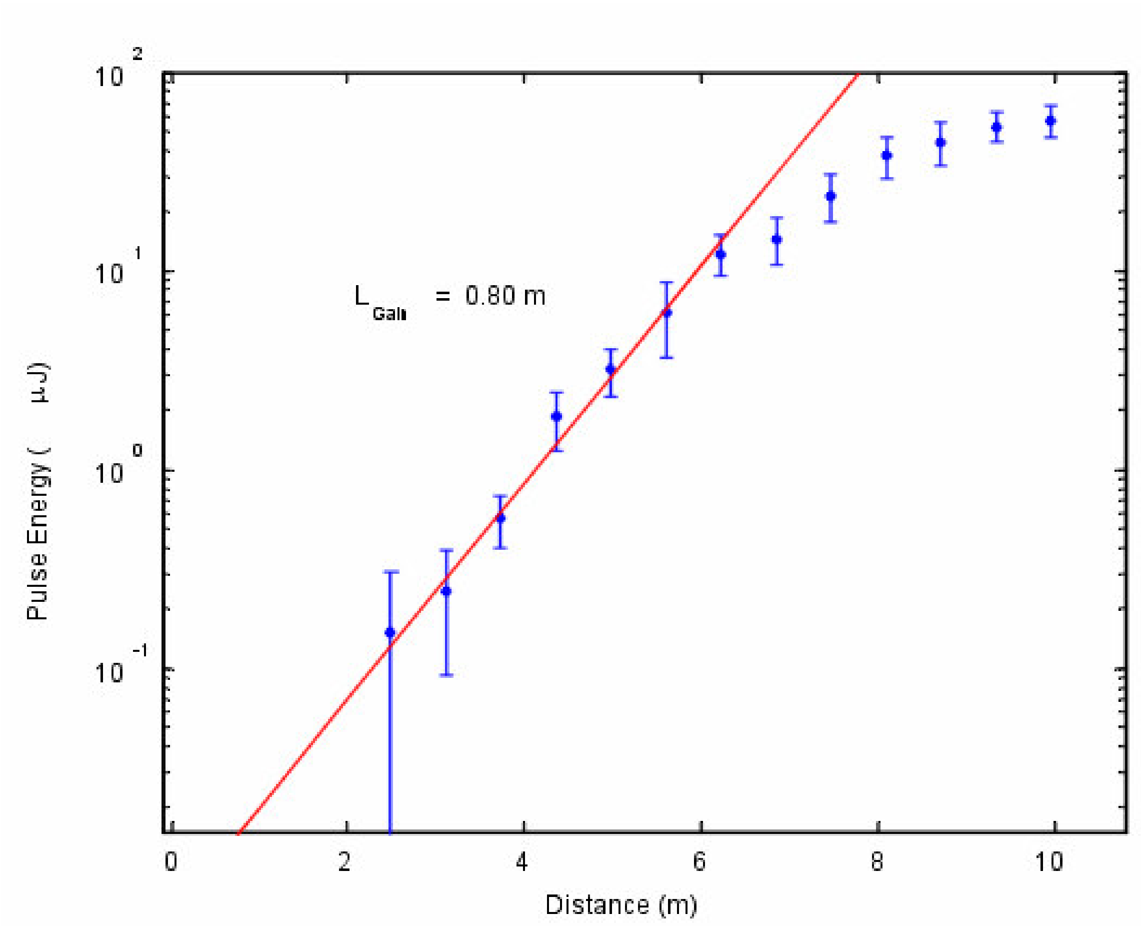
HGHG Experiment



HGHG from 800 nm→266 nm,
Output at 266 nm: ~ 120μJ,
e-beam: 300 Amp, 3 mm-mrad,
Energy 176MeV

Output at 88 nm ~ 1 μJ
On-going Experiment Application in Chemistry

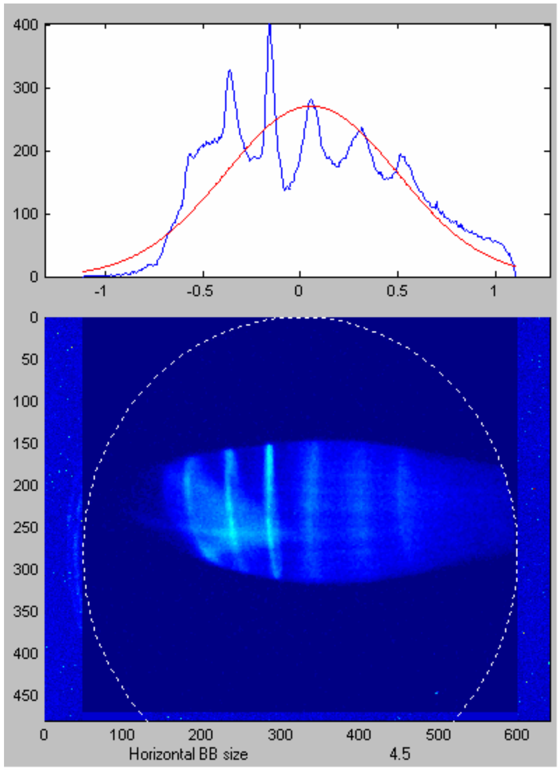
HGHG power vs. distance (266 nm)



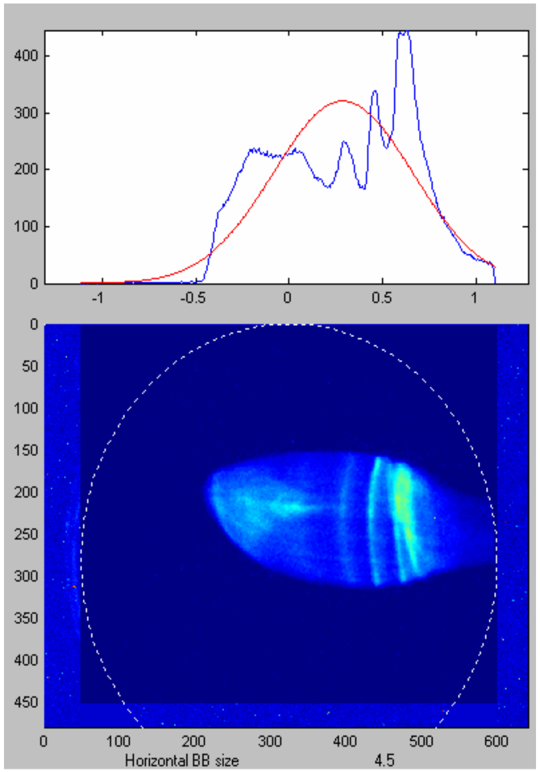
E-beam: 300 pC 4.7 μm (rms) 1.ps (FWHM)

Power measured by kicking beam off axis agree with photo-diode measurement along NISUS

Bunch Length Measurement by Zero Phasing (12/2002)



Head Left



Head Right

•Projection of energy chirped pulse on energy axis, so the profile is not current but related to current.

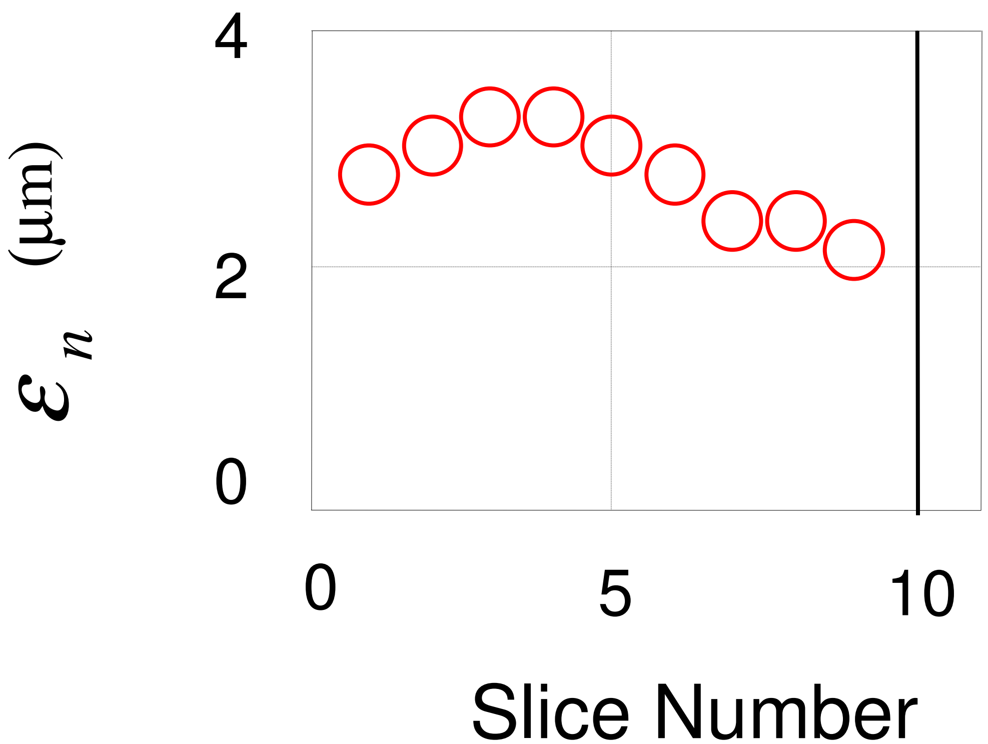
•Ripples are due to small energy modulation, not large density modulation

•Average current: 300pC/1ps =300 Amp

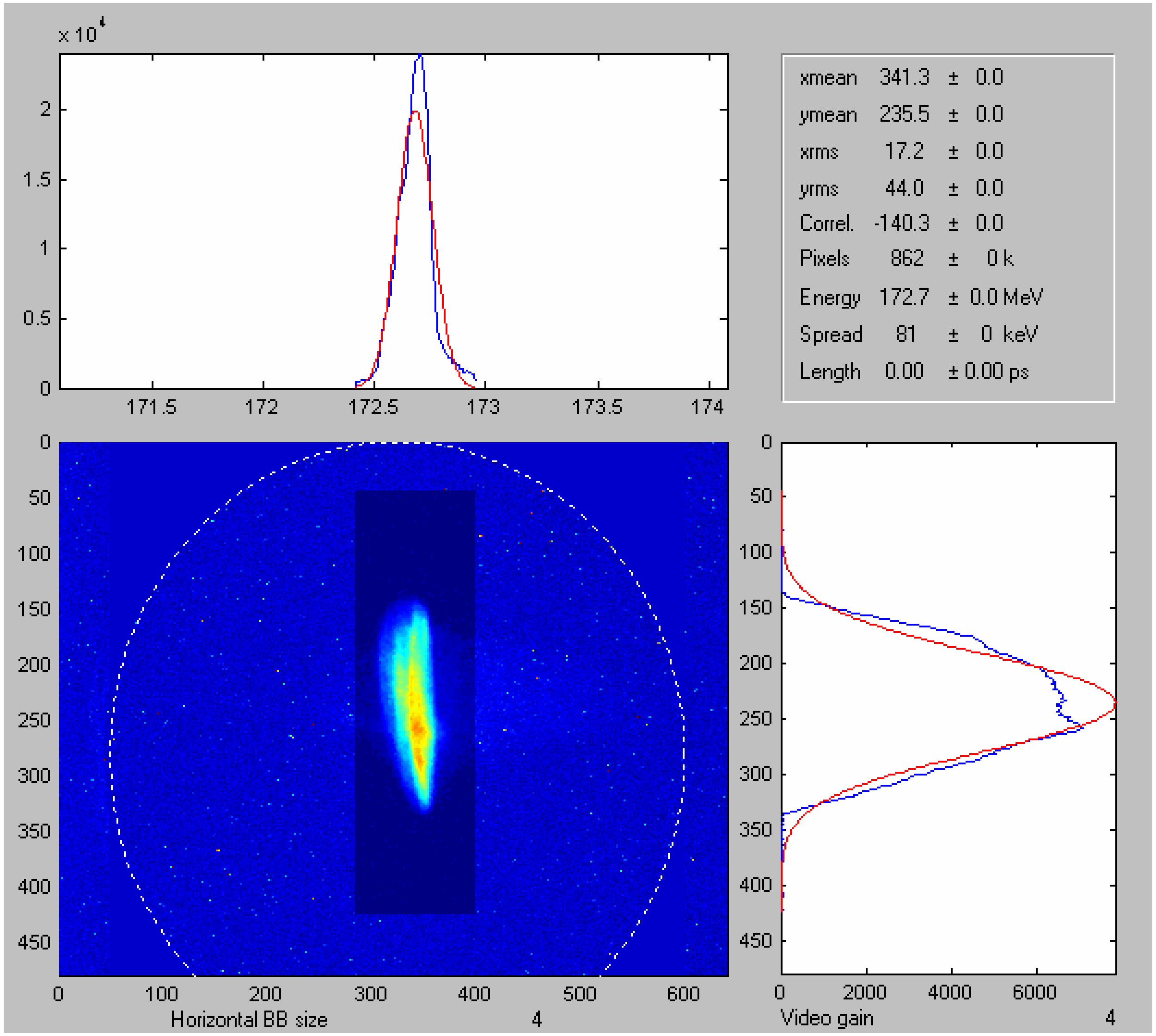
Slice Emittance Measurement Without Compression

Integrated emittance = 4.8 µm, Q=200 pC

W.Graves, Data from 3/25/02.



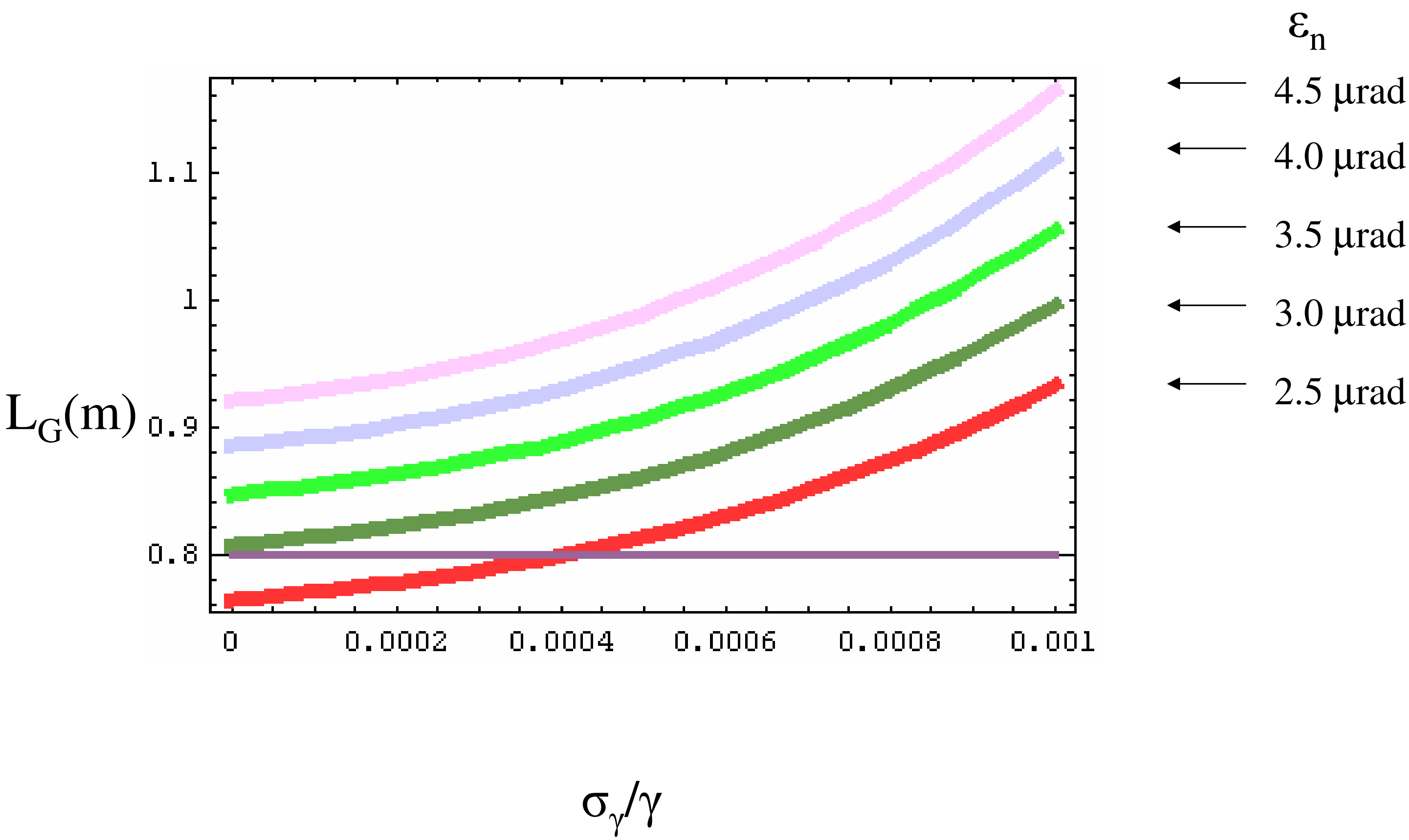
Global energy spread measurement result: 5×10^{-4}



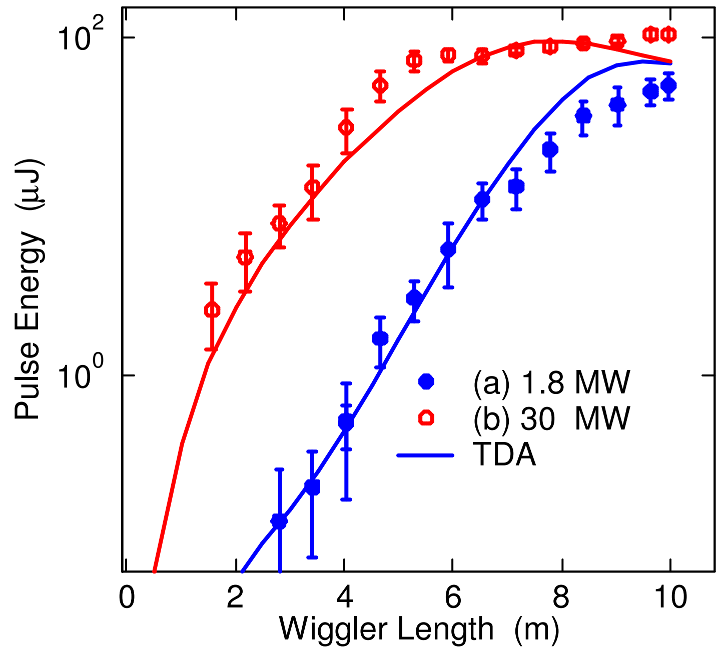
Based on measurement of 12/11/2002: L_G =0.8m ,

current = 300 amp, slice emittance ε_n< 4mm-mrad

Theory : local energy spread (rms) < 0.05%



Two sets of data compared with TDA Simulation



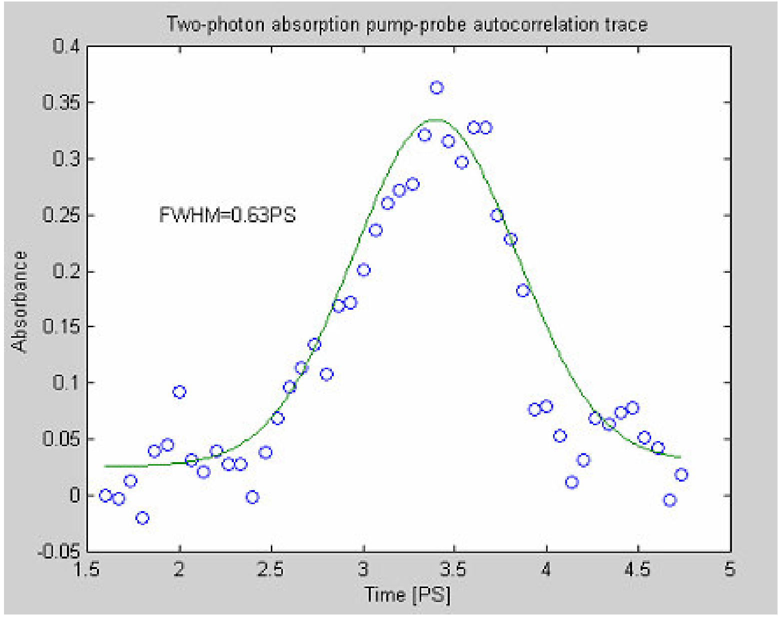
Current 300 A, Energy spread $\sigma_\gamma/\gamma = 1\times10^{-4}$, Dispersion $d\psi/d\gamma = 8.7$

(a) 12/11/02 Model: P_{in}=1.8MW pulse length 0.6 ps, slice emittance 2.7 mm-mrad $d\psi/d\gamma = 8.7$

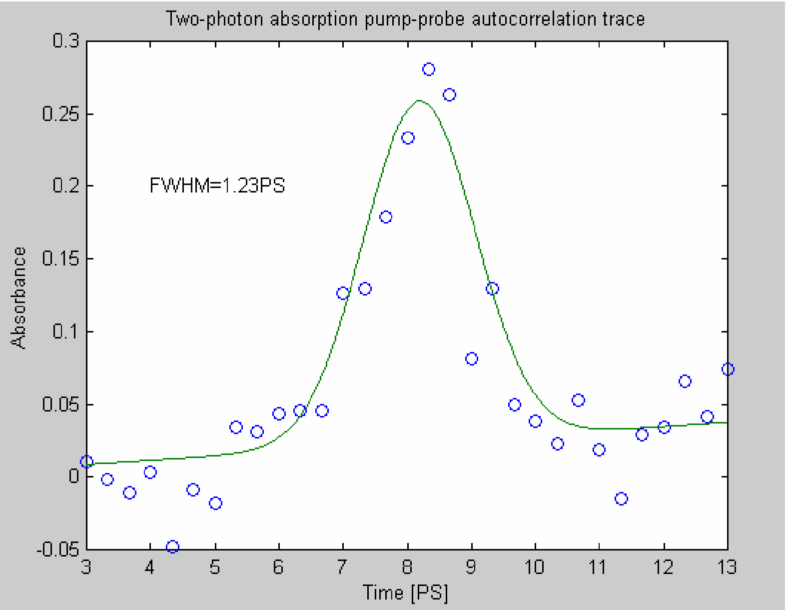
(b) 3/19/03 Model: P_{in}=30MW pulse length 1 ps, projected emittance 4.7 mm-mrad, $d\psi/d\gamma = 3$

Whole bunch contributes to the output.

Autocorrelation Pulse Length Measurement (Zilu, 2003)



(a)



(b)

current 300 Amp, energy spread $\sigma\gamma/\gamma = 1\times10^{-4}$, dispersion $d\psi/d\gamma = 8.7$

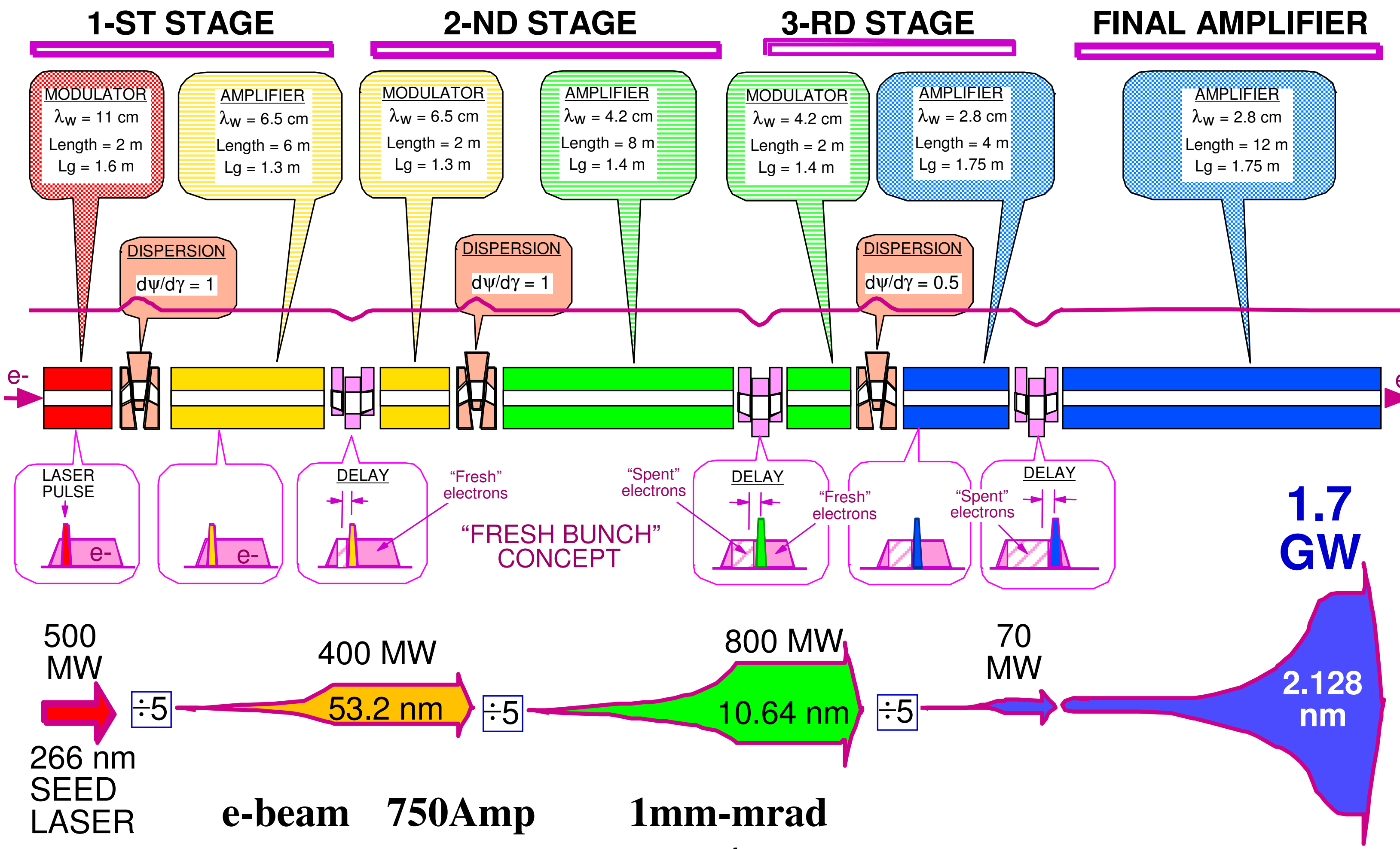
(a) **12/11/02 Model**: P_{in}=1.8MW pulse length 0.6 ps, slice emittance 2.7 mm-mrad

(b) **3/19/03 Model**: P_{in}=30MW pulse length 1 ps, projected emittance 4.7 mm-mrad

Whole bunch contributes to the output

R&D Towards Cascading HGHG: One of the Earlier Calculated Schemes

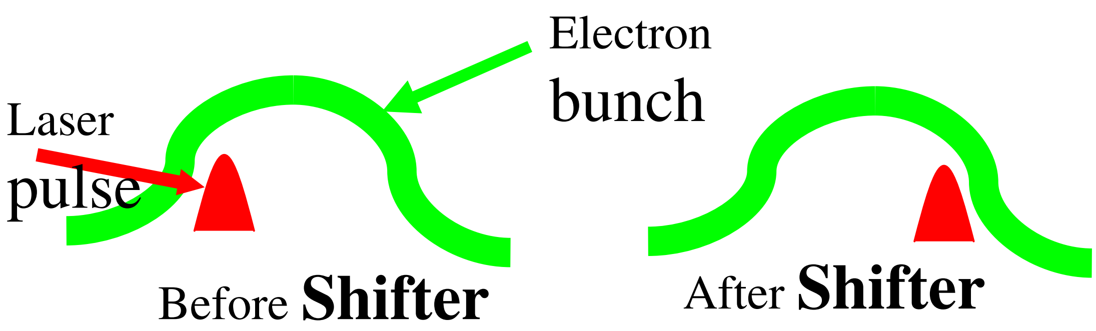
A Soft X-Ray Free-Electron Laser



e-beam 750Amp 1mm-mrad

2.6GeV $\sigma_\gamma/\gamma = 2\times10^{-4}$ **total** L_w **=36m**

Fresh Bunch Technique



Technical issues:

- Time jitter of seed << electron bunch length
- Reduce number of stages: higher harmonic, smaller local energy spread
- Shorter seed laser pulse

Some of the experiments that can be carried out at DUVFEL to address the associated issues in the Cascading HGHG scheme

1. Chirped Pulse Amplification
   study how to generate short pulse in HGHG

2. 8’th harmonic HGHG (800nm→100nm)
   possibility to reduce the number of stages of HGHG
   study how small the local energy spread is
   relation of coherence with harmonic number?

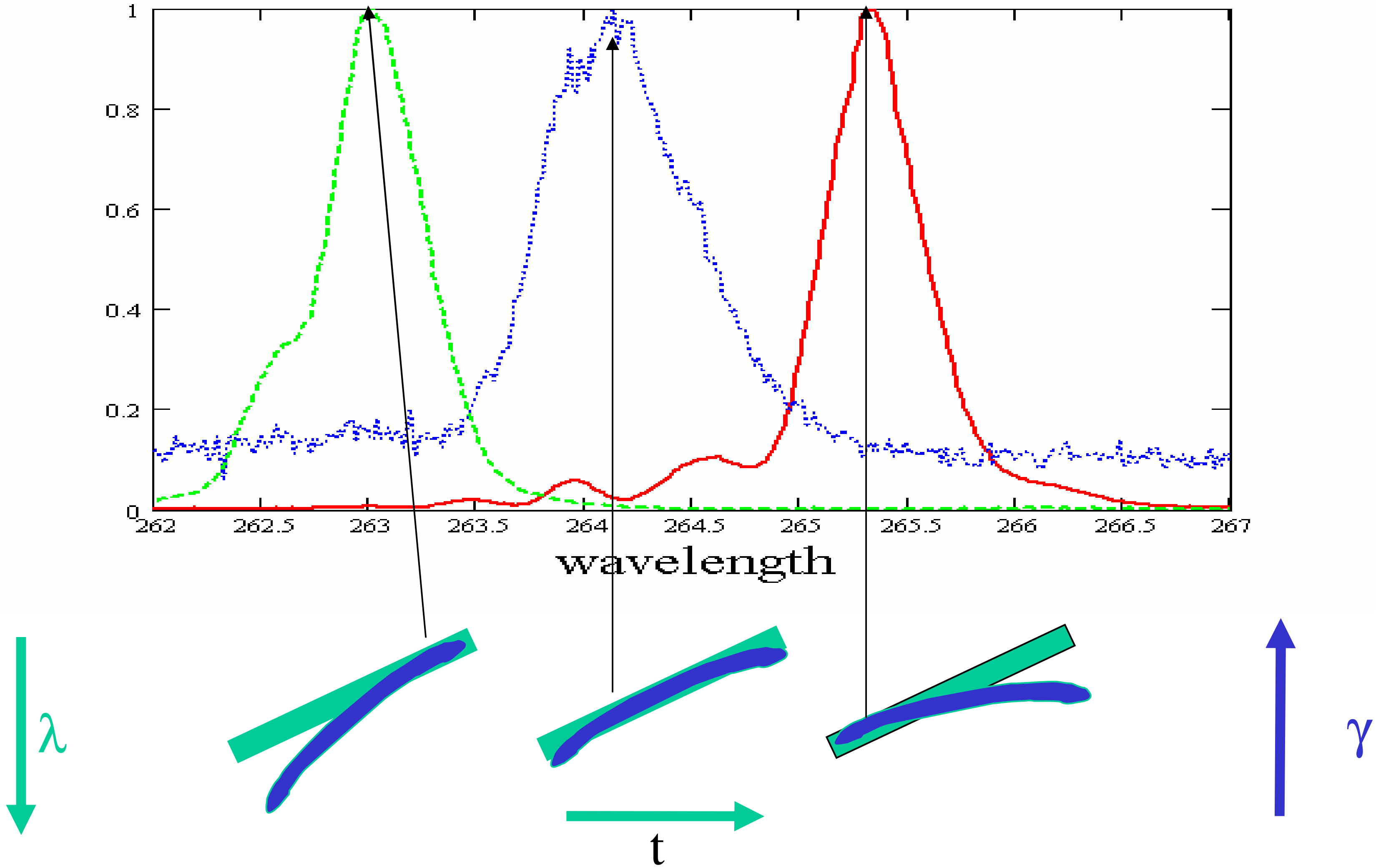
3. HGHG with seed shorter than electron bunch length
   study the jitter and its relation to pulse shape

4. Regenerative synchronization of seed pulse and electron bunch
   accurate synchronization is essential for cascading

5. Cascading using NISUS+VISA: 400nm→100nm→50nm.
   Proof-of-principle experiment for cascading

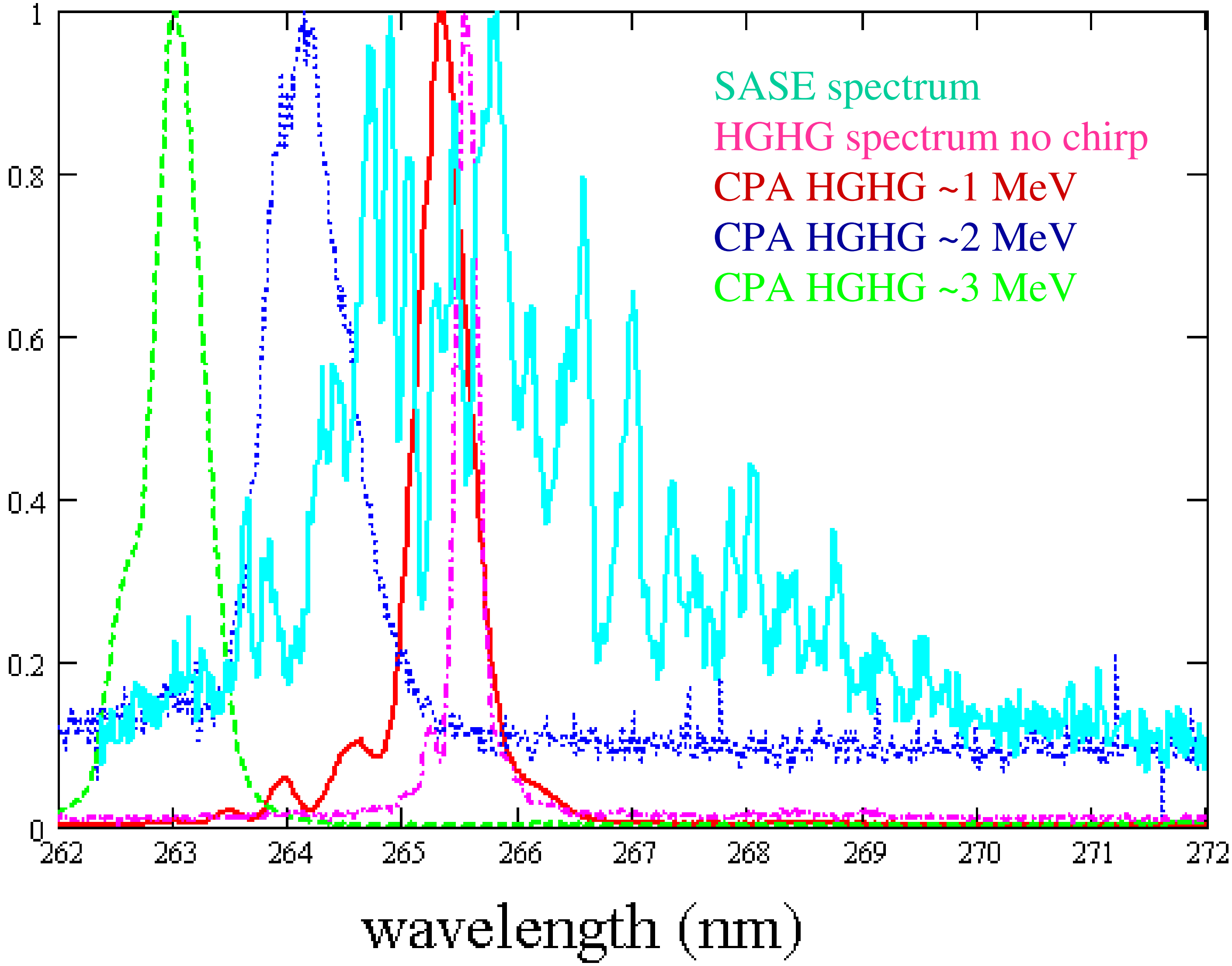
6. Tuning of HGHG without changing seed (Timur Shaftan)
   feasibility study at DUVFEL

Preliminary Data of CPA HGHG Spectra (A. Doyuran, et al., 8. 2003)

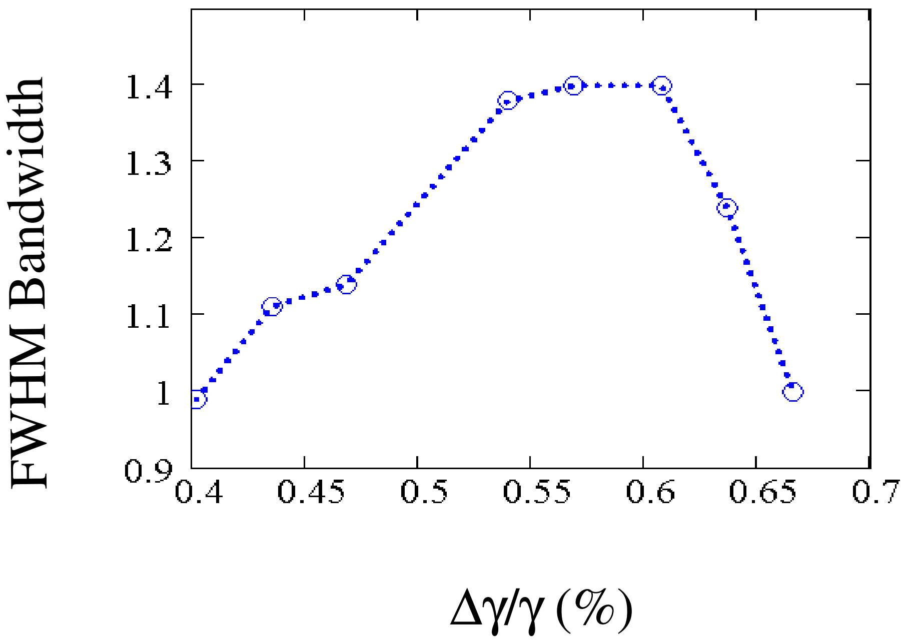


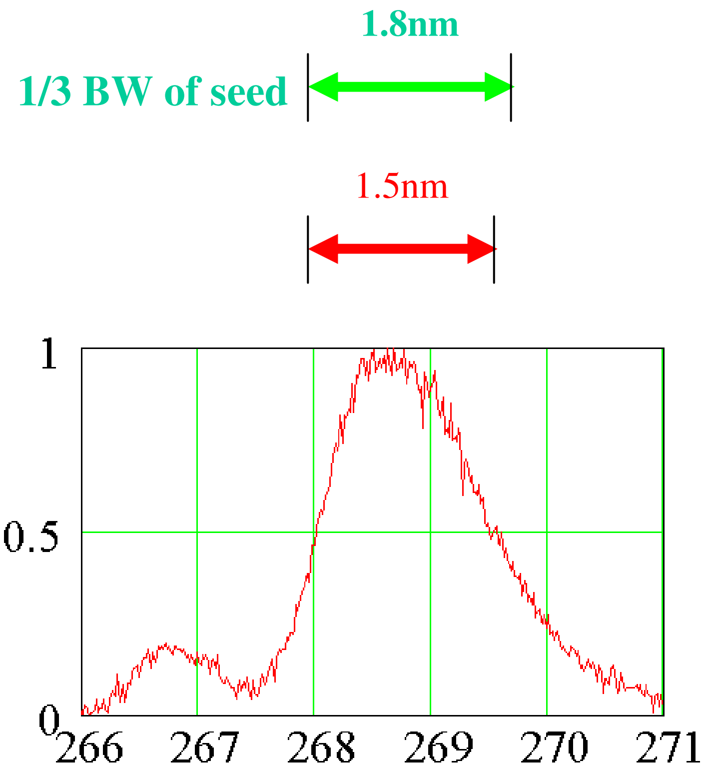
Interpretation of 3 sets of measurements: effect of RF curvature; the second matched e-beam chirp to seed chirp

Chirped and Unchirped HGHG spectra



Bandwidth vs Chirp





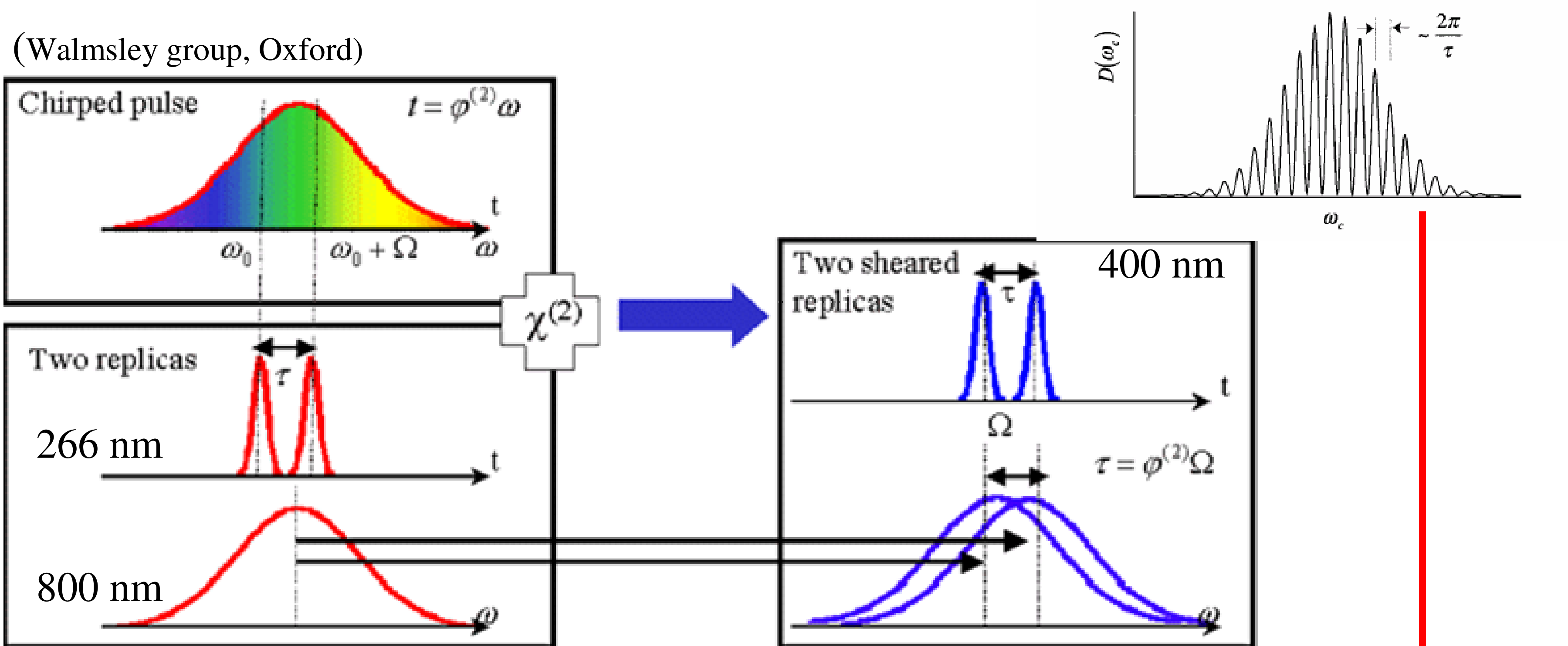
Seed bandwidth is 5.5 nm currently, thus 1.8 nm is expected at third harmonic.

Spectrum at $\Delta\gamma/\gamma = 0.62$ %

- **Next: measurement of phase distortion**
- **CPA: expected pulse length > 50fs (B. Sheehy, Z. Wu)**
- **R&D: CPA at 100 nm?**

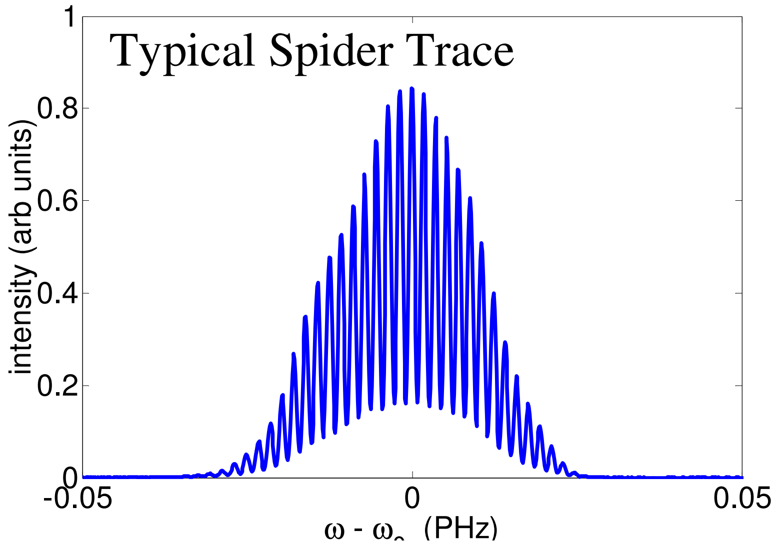
Measuring the spectral phase: SPIDER
(Spectral Interferometry for Direct Electric-Field Reconstruction)

(Walmsley group, Oxford)



$$D(\omega_c) = |\tilde{E}(\omega_c - \Omega)|^2 + |\tilde{E}(\omega_c)|^2 + 2|\tilde{E}(\omega_c - \Omega)\tilde{E}(\omega_c)| \cos[\phi_\omega(\omega_c - \Omega) - \phi_\omega(\omega_c) - \tau\omega_c].$$

Spidering a laboratory 266 nm source (B. Sheehy, Z. Wu_)

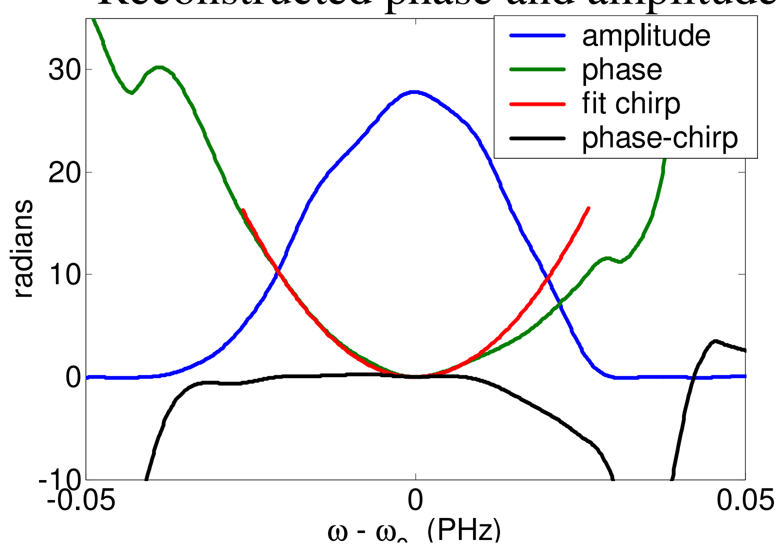


•Undercompress a 100 femtosecond 800 nm Ti:Sapph chirped-pulse-amplification system

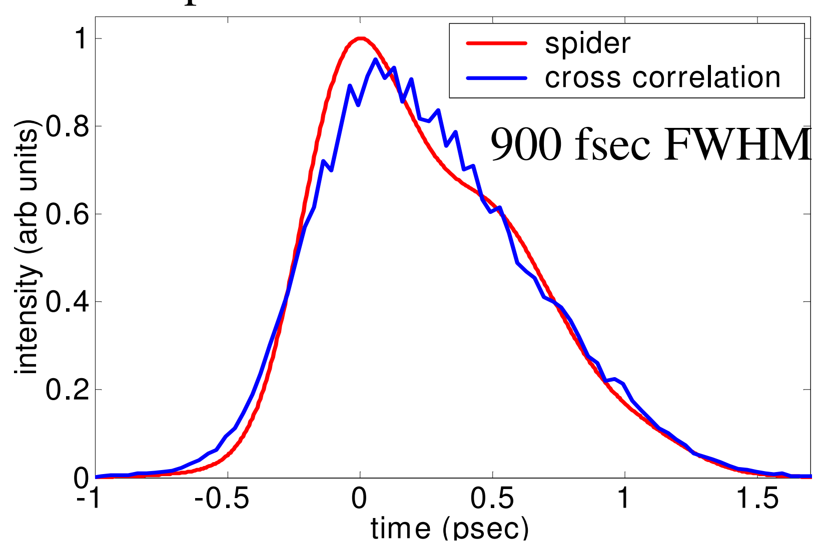
• Frequency-triple in BBO to 266 nm(spoil phase matching to create an asymmetry in the time profile)

• Compare scanning multi-shot x-correlation of the 266 nm and a short 800 nm pulse with the average reconstruction, convolved with 250 fsec resolution of the x-correlator

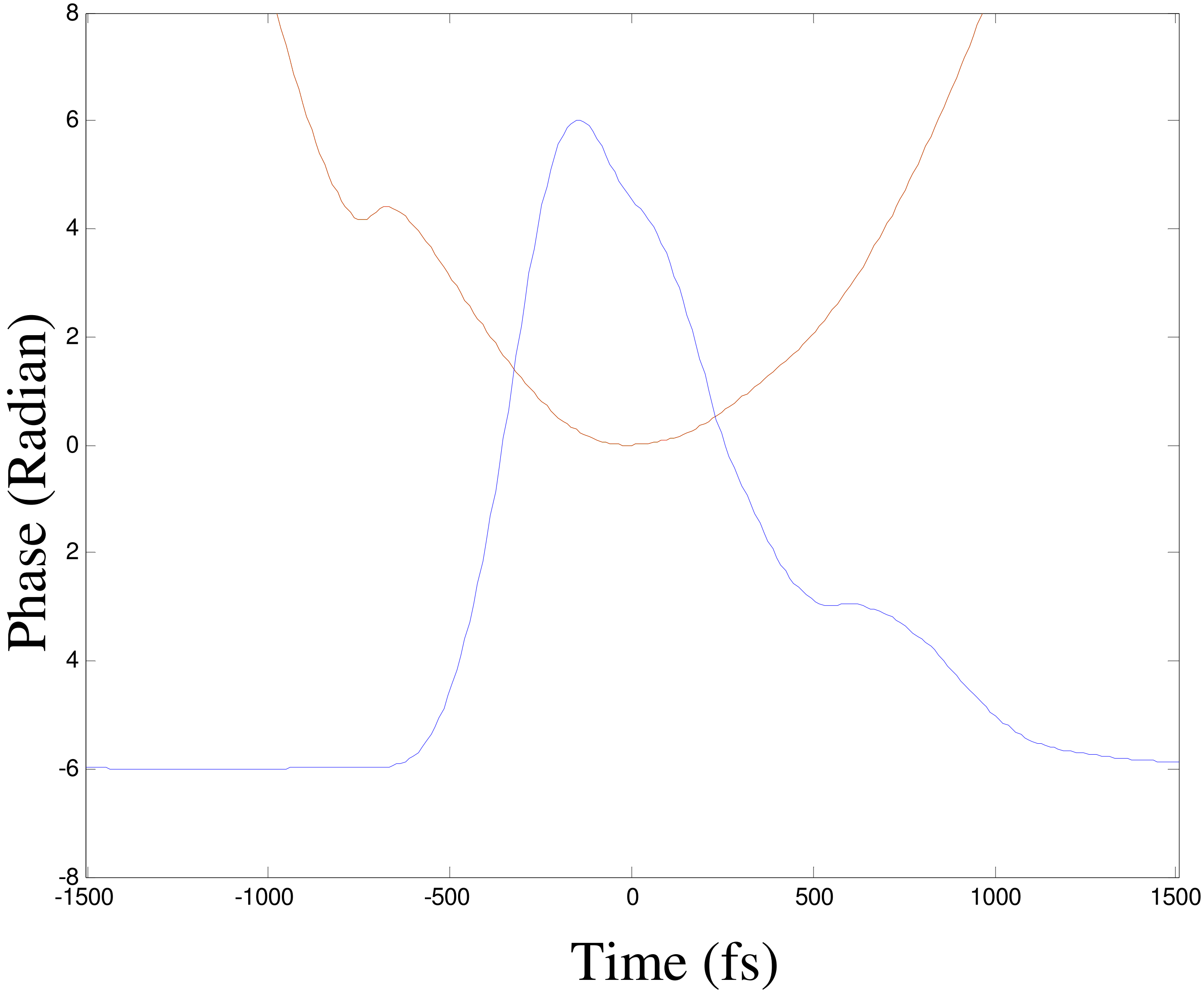
Reconstructed phase and amplitude



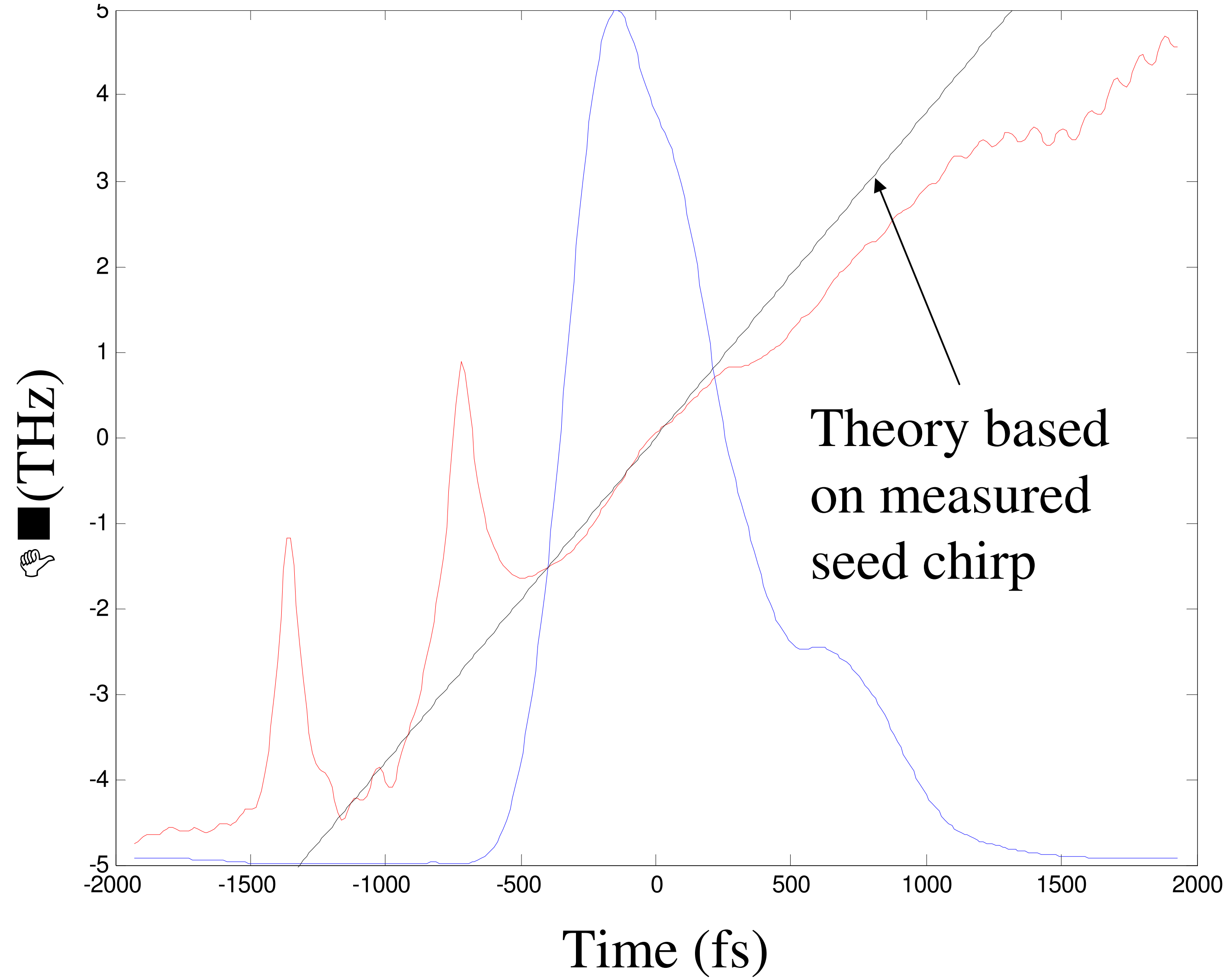
Comparison with x-correlation



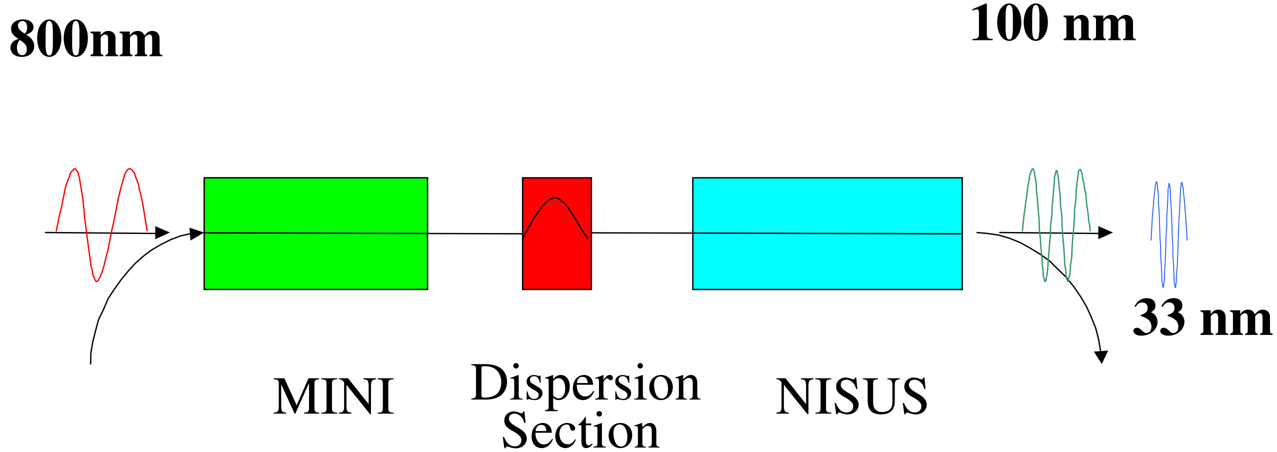
Preliminary Data of SPIDER for a chirped HGHG
Phase and amplitude vs. time



Preliminary Data of SPIDER for a chirped HGHG
Frequency change vs. time (electron beam energy chirp unmatched)

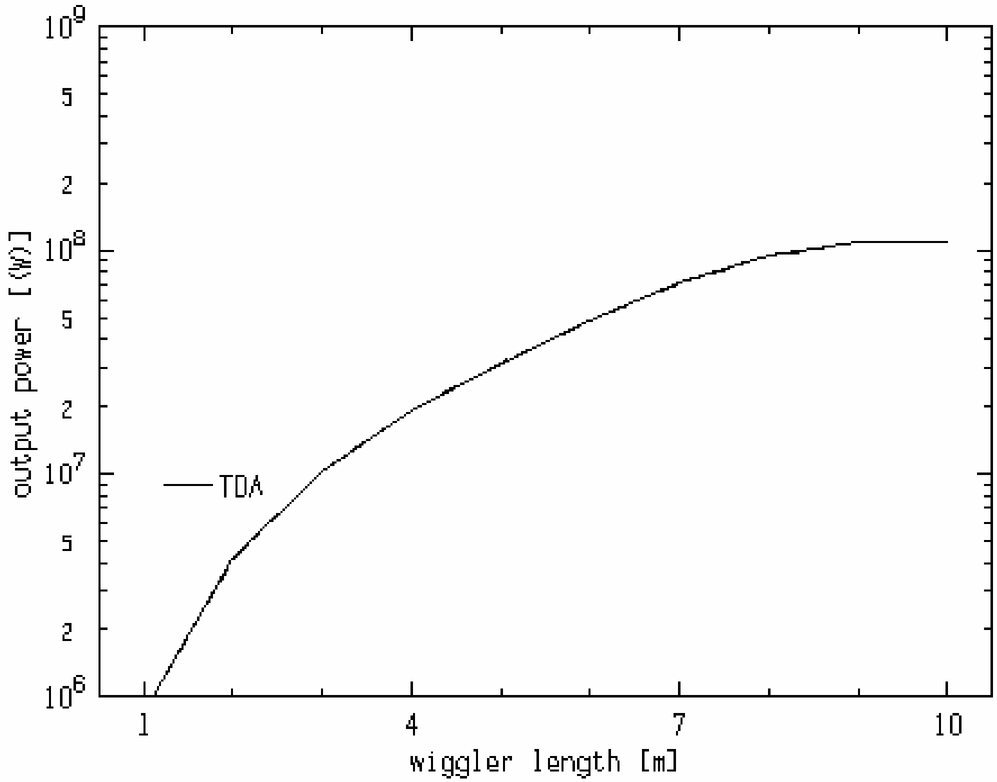


Possible Step: 8^{th} Harmonic HGHG



- Electron beam energy upgrade to 300 MeV
- Need to reduce modulator vacuum chamber gap
- Increase flexibility of wavelength tuning

Power vs. distance for 100 nm in HGHG from 800nm

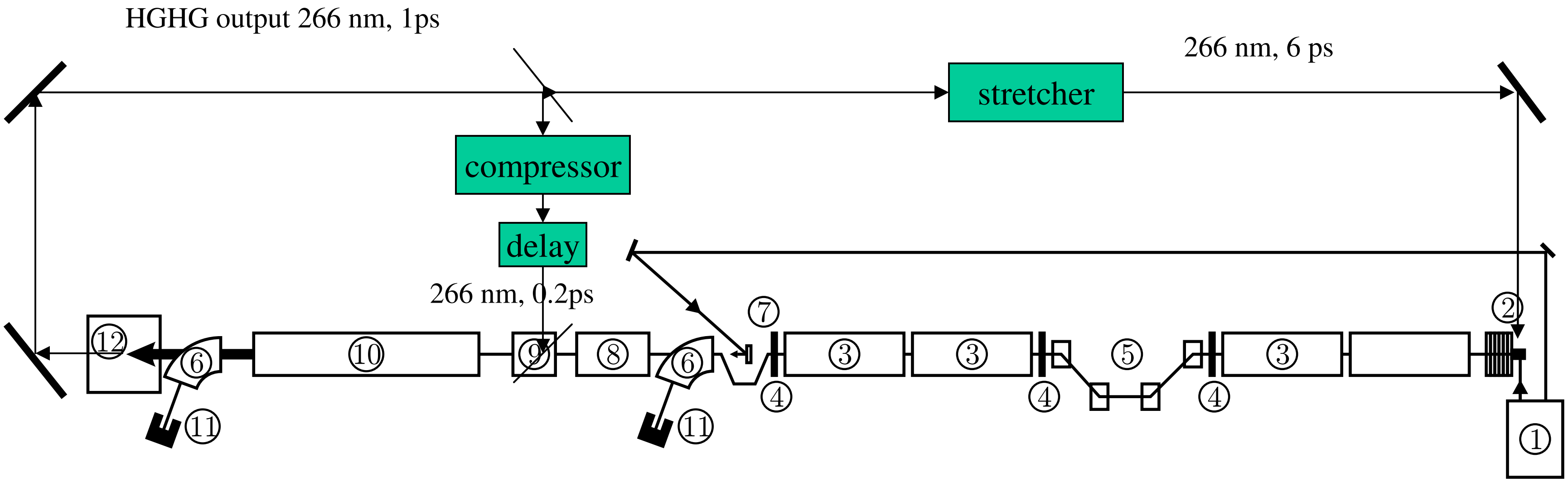


- Calculated for the same beam conditions as the present HGHG:

  current 300 Amp, energy spread $\sigma\gamma/\gamma = 1\times10^{-4}$, slice emittance 2.7 mm-mrad input seed with 60 MW

- Going for higher harmonic and increase dispersion will lower the upper limit of the local energy spread estimate, possibly below 1×10^{-4}: 5×10^{-5} ?

Regenerative synchronization of seed pulse and electron bunch (L.H.Yu, FEL2003)



•The jitter between the seed pulse and the electron bunch will be reduced by the compression ratio

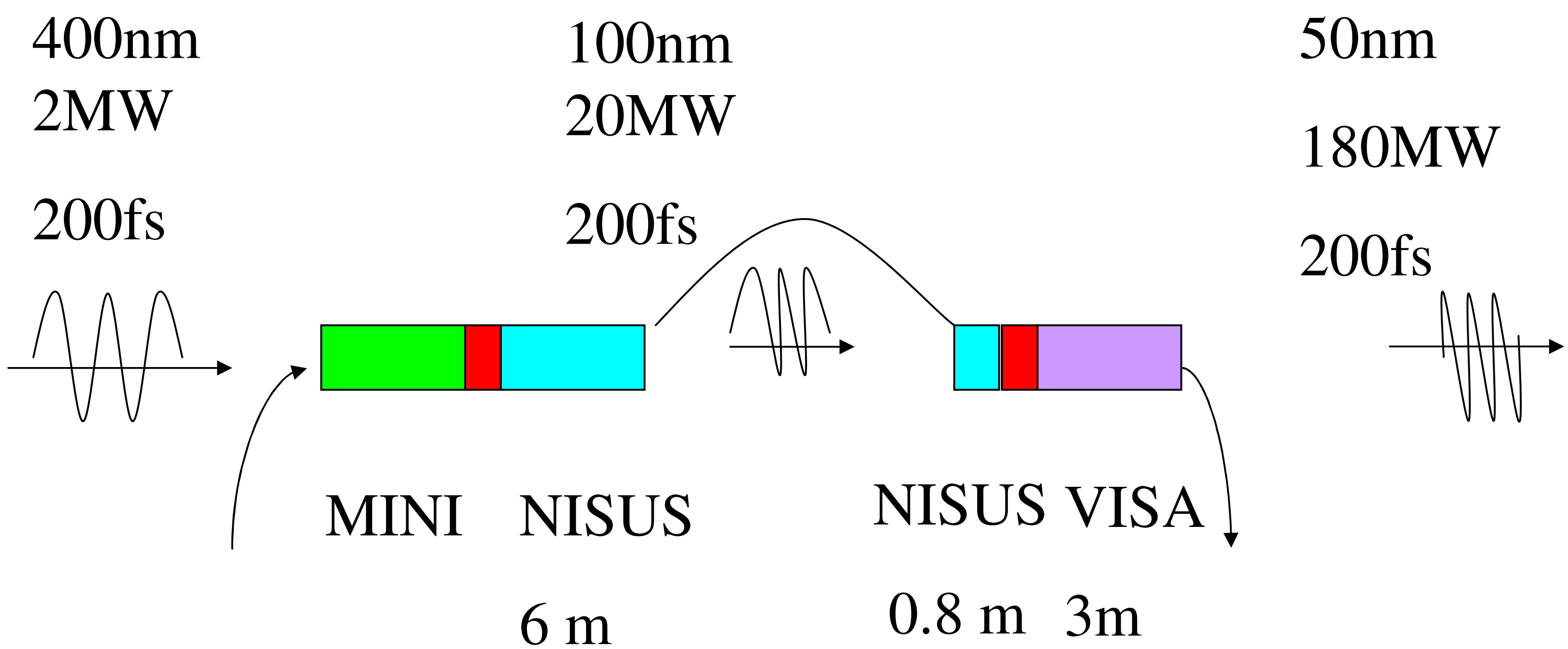
•It is possible to reduce jitter to below 50fs: an unprecedented precision. Important for multi-stage cascading to X-ray FEL

•Can be tested without significant cost under present conditions

•Energy fluctuation is also reduced by the same ratio

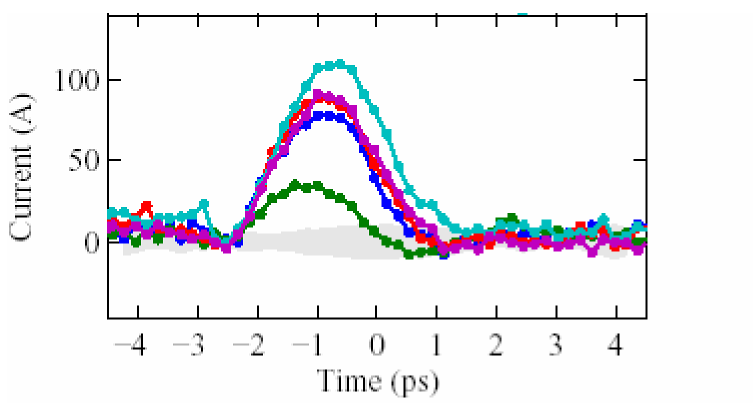
Cascading HGHG Using Fresh Bunches

Under the present e-beam Conditions



e-beam **1ps**
300Amp **2.7mm-mrad**
288MeV $\sigma_\gamma/\gamma = 1\times10^{-4}$

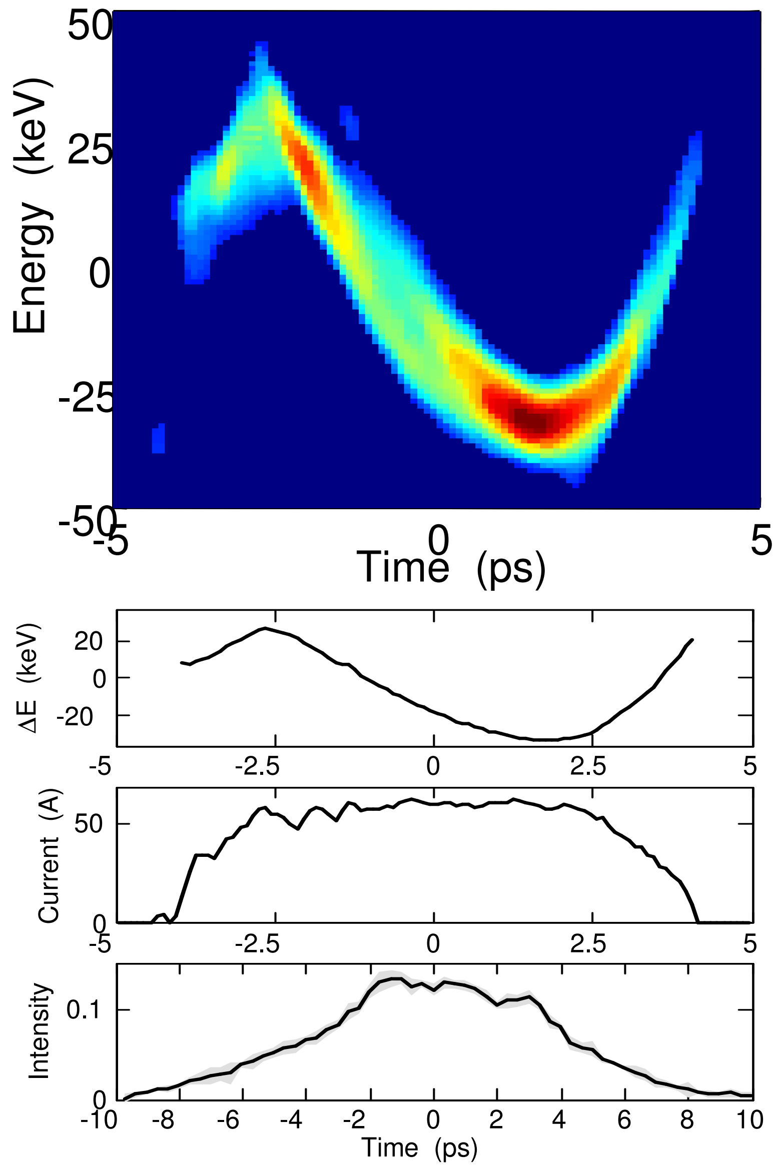
Electro-optical Measurement by Henrik Loos & Brian Sheehy showed the time jitter between electron bunch and seed laser is ~ 300fs.



- Measuring timing jitter between electron beam and laser is important in externally seeded FEL schemes like HGHG
- Single shot measurement decouples jitter from pulse length
- Estimated jitter from this electro-optic measurement between electron beam and seed laser is rms 170 fs
- Jitter between low-level RF and Ti:Sapphire oscillator is 200 fs
- Energy jitter obtained in dipole spectrometer corresponds to 1 ps RF amplitude/phase jitter

Tomography of electron bunch distribution by Henrik Loos 12/2/03

Reconstruction Uncompressed Bunch



Reconstruction compressed Bunch

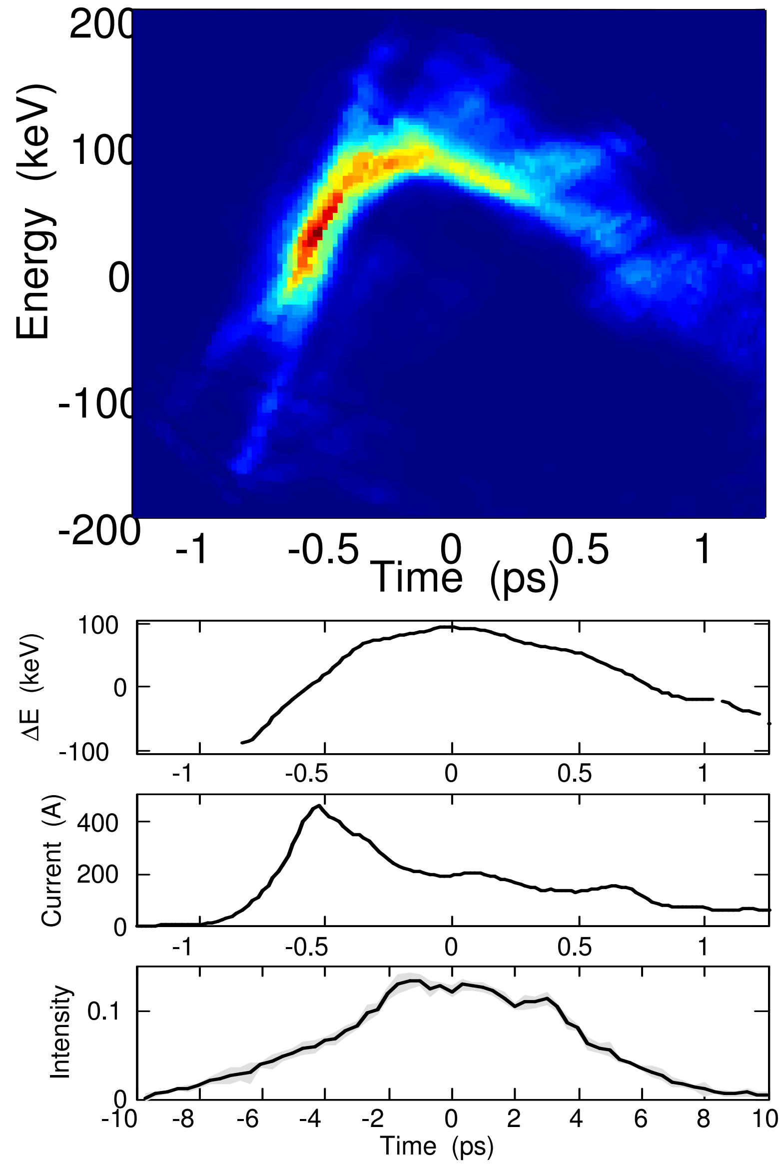
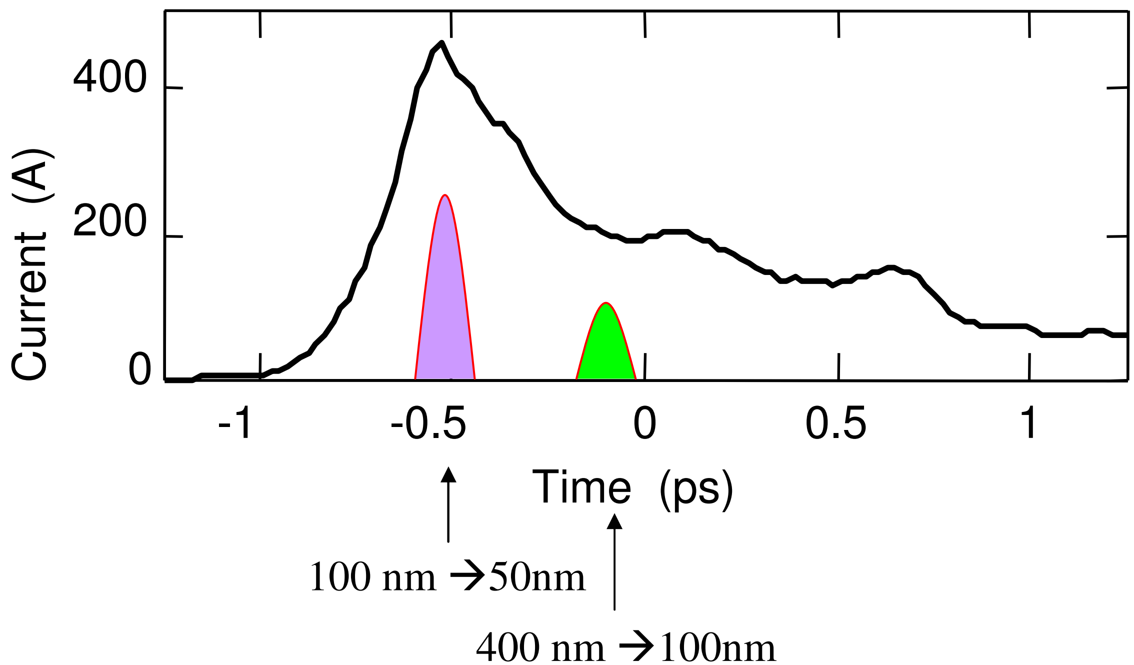


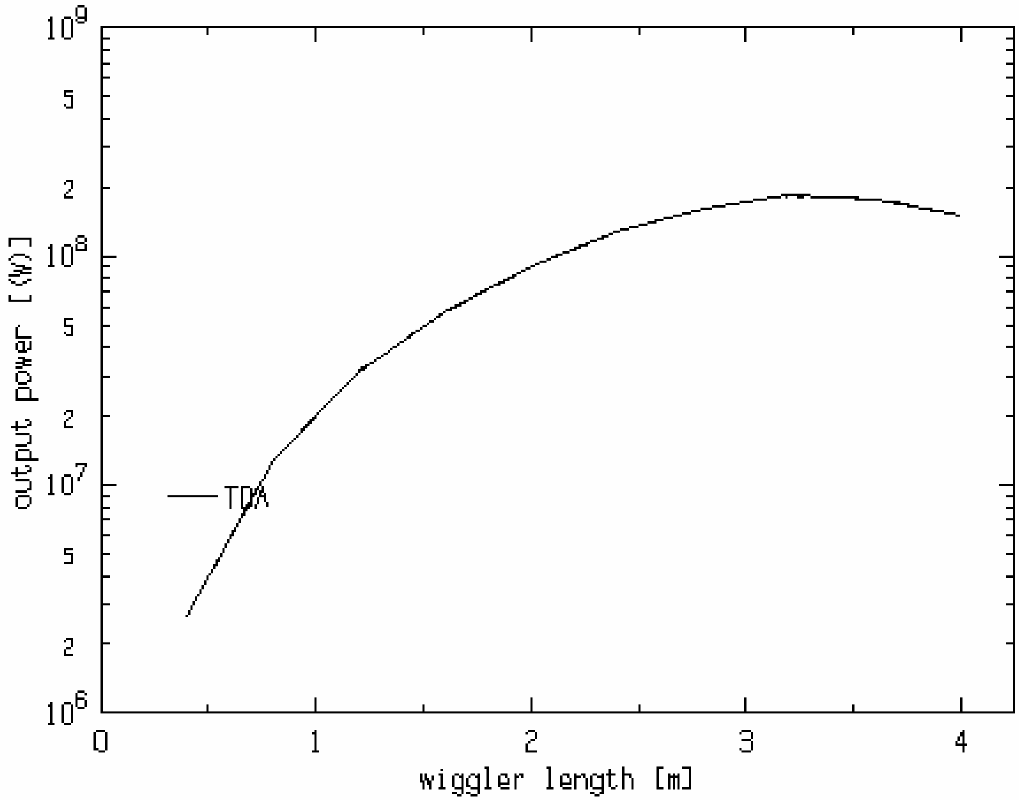
Illustration on how to use the electron bunch twice during cascading of HGHG



Time (ps)

Cascading HGHG from 400nm to 100 nm, then

to 50 nm, input 20MW, dispersion=3.6

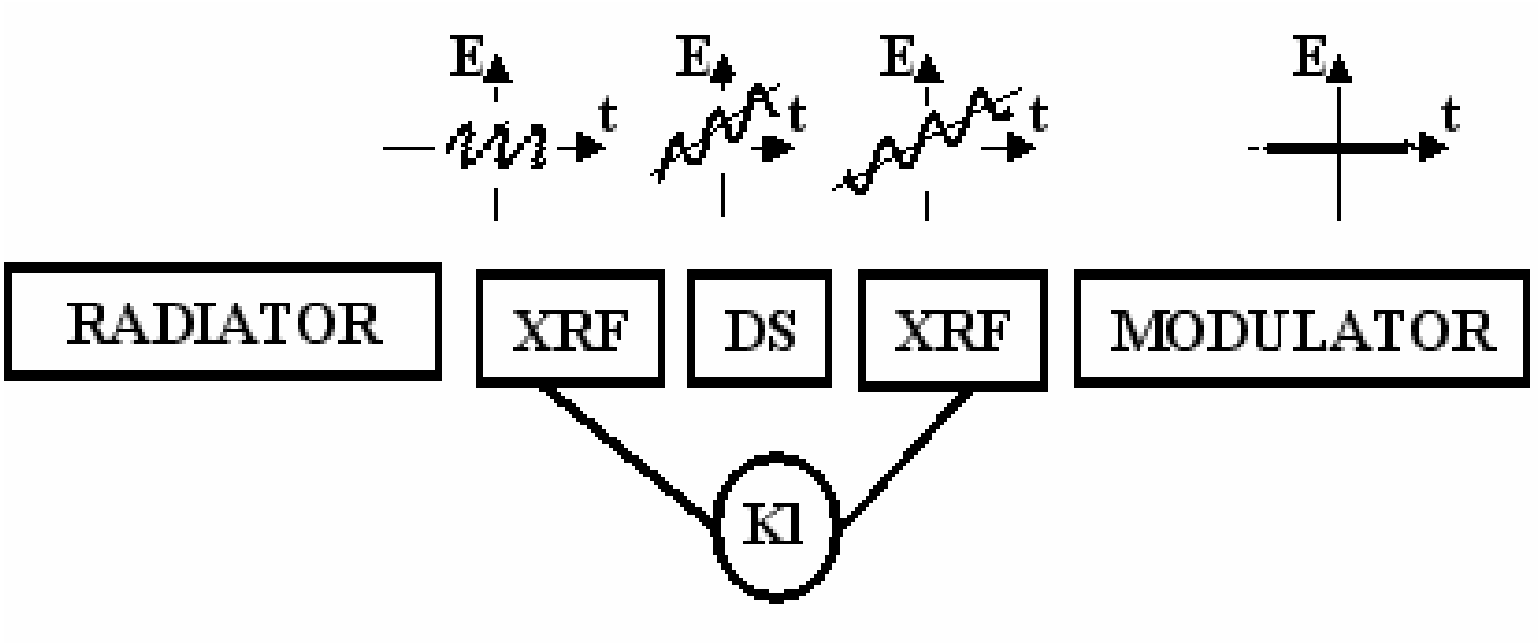


If we improve beam current from 300 Amp

to 600 Amp, the saturation is reached before 2 m in VISA

HGHG with variable wavelength

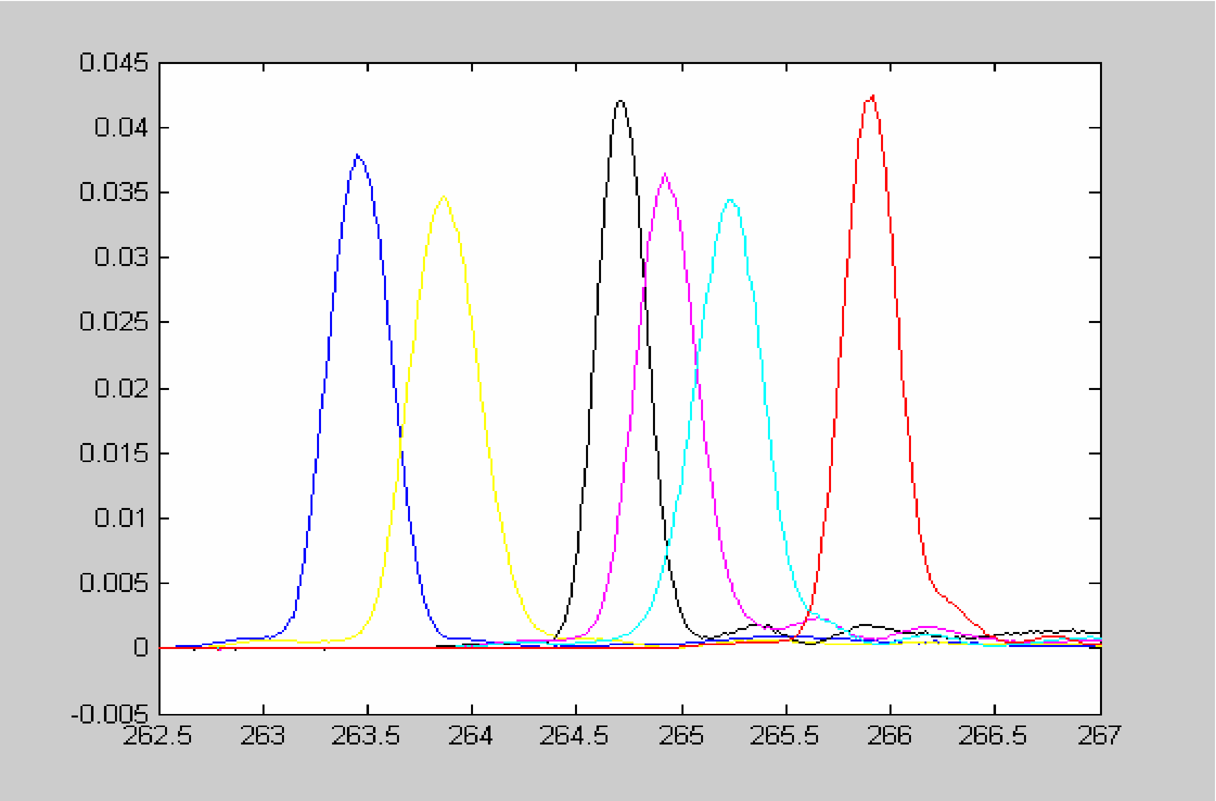
(Timur Shaftan, 2004)



There is a small compression of the electron bunch in the dispersion section, hence the wavelength is also slightly compressed.

Single-Shot spectra for different chirps for the same seed wavelength showed different output wavelengths

(Timur, Brian, Henrik, Zilu 2004)



Possible experiment in near future: increase dispersion→ increased tuning range

Summary

- Analysis of the present HGHG experiment provides estimates for the operating parameter range
- Based on the roughly determined beam parameters, we suggest some of the experiments that can be carried out at DUVFEL to address the associated issues in the cascading HGHG scheme:

1. Chirped Pulse Amplification
2. 8’th harmonic HGHG (800nm→100nm)
3. HGHG with seed shorter than electron bunch length
4. Regenerative synchronization of seed pulse and electron bunch
5. Cascading using NISUS+VISA: 400nm→100nm→50nm.
6. Tuning of HGHG without changing seed (Timur Shaftan)