

# An experimental demonstration of superradiance in a single-pass seeded FEL at BNL-NSLS

T. Watanabe, X.J. Wang, D. Liu, J.B. Murphy, J. Rose, T. Shaftan, Y. Shen,  
T. Tsang and L.H. Liu, BNL, USA  
L. Giannessi and S. Spampinati, ENEA, Italy  
P. Musumeci, Universita di Rome, Italy  
S. Reiche, UCLA, USA

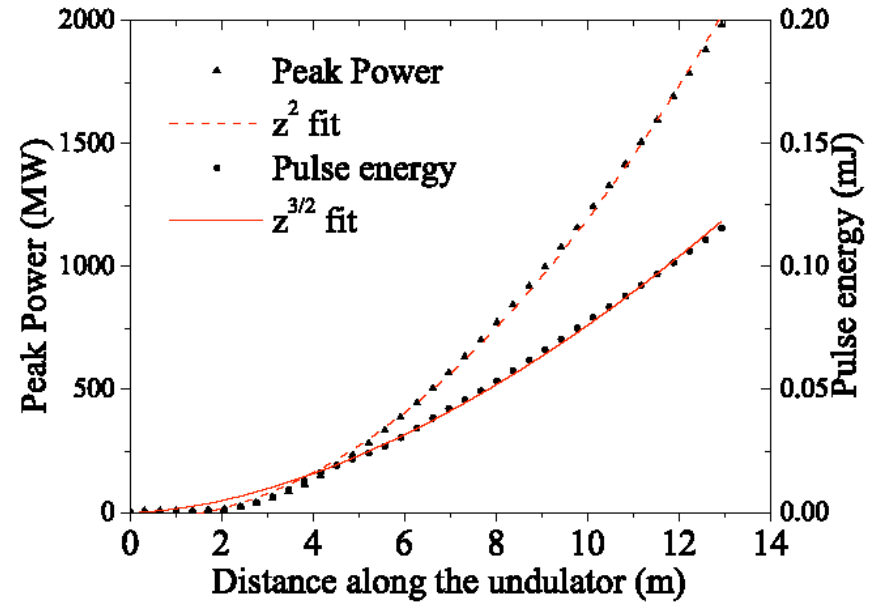
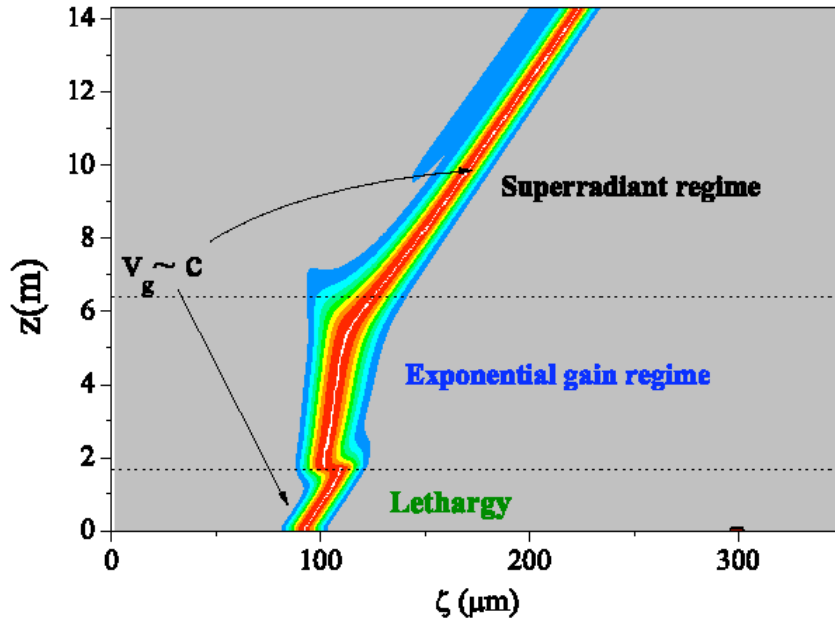
## Outline

- Superradiance in a single-pass seeded FEL
- Numerical simulation
- **Experimental demonstration**

# Superradiance in FEL

- R. Bonifacio and F. Casagrande, NIM A 239 (1985).
- R. Bonifacio, et al, Phys. Rev. A 40 (1989) 4467.
- L. Giannessi, et al, J. Appl. Phys. 98, 043110 (2005).

Seed laser pulse duration  $\ll$  E-beam pulse duration



Peak power	Pulse energy	Pulse duration
$P \propto z^2$	$E \propto z^{3/2}$	$\sigma_{sr} \propto z^{-1/2}$

# Superradiance in FEL

- R. Bonifacio and F. Casagrande, NIM A 239 (1985).
- R. Bonifacio, et al, Phys. Rev. A 40 (1989) 4467.
- L. Giannessi, et al, J. Appl. Phys. 98, 043110 (2005).

Seed laser length  $\ll$  E-beam length

Longitudinal profiles of FEL pulse in superradiance regime

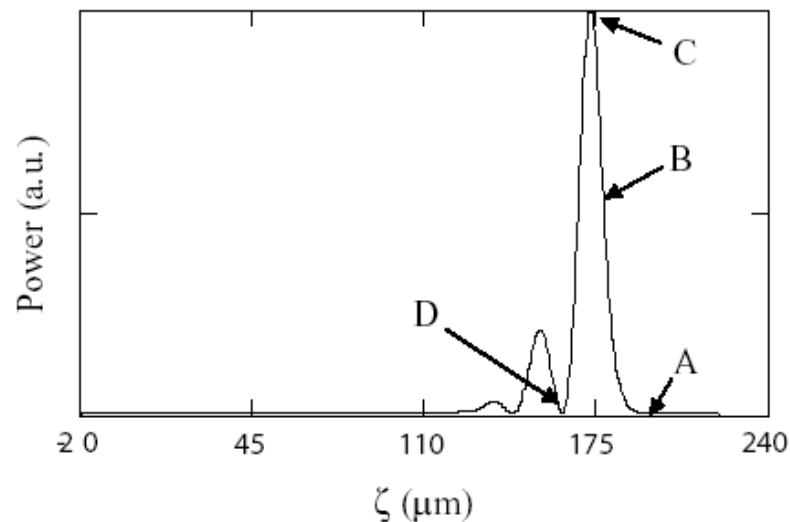
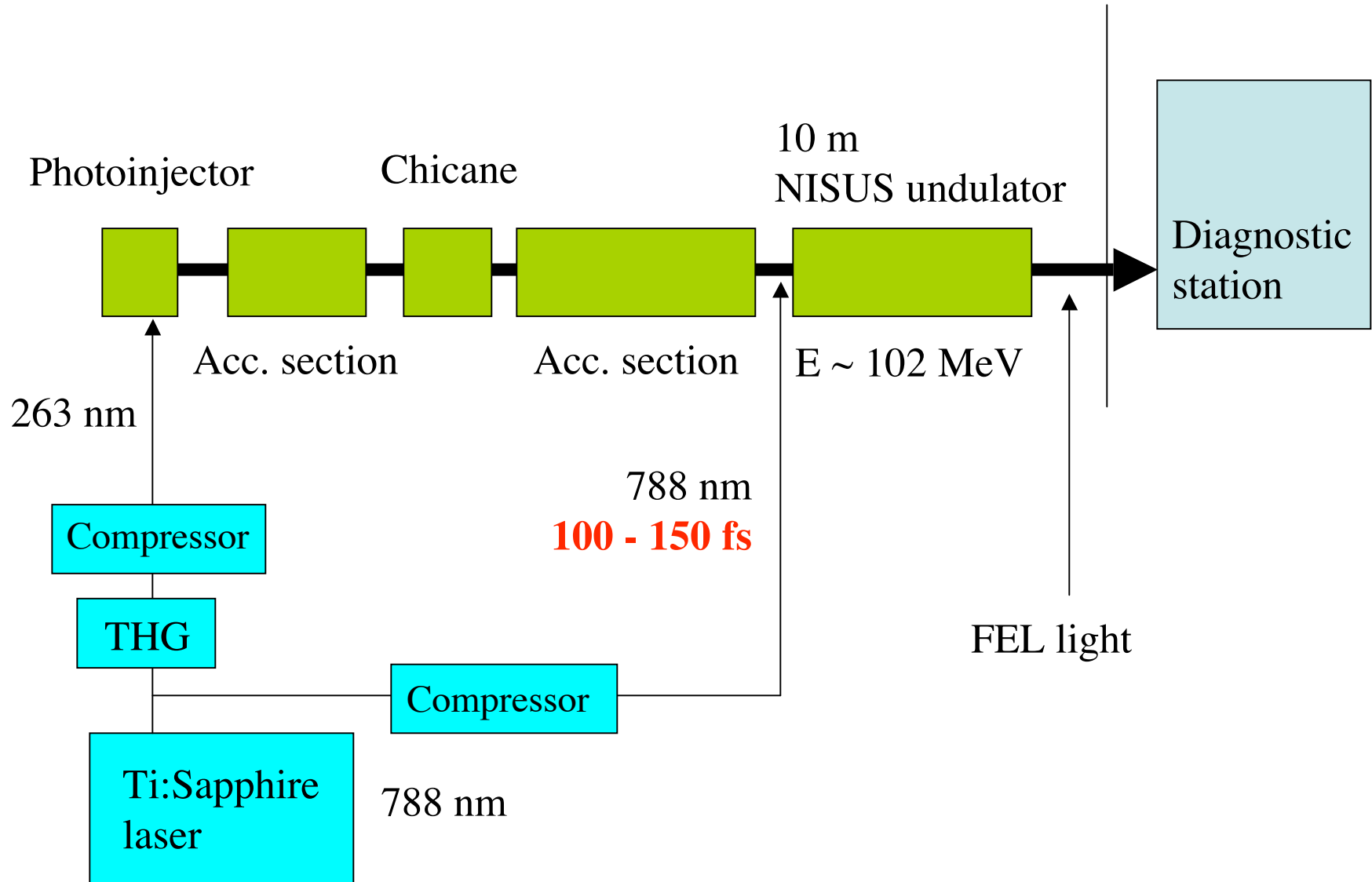


FIG. 2: Longitudinal profile of the radiation pulse in the superradiant regime.

# Superradiant experiment at BNL-SDL



# NISUS undulator + short seed pulse @ SDL

$K=1.07$

Undulator period = 3.89 [cm]

E-beam energy = 102 [MeV]

Norm. emittance = 5.5 [mm.mrad]

Energy spread = 0.05 [%]

Beam size = 172 x 139 [ $\mu\text{m}$ ]

Peak current = 350 A

E-beam duration (FWHM) = 2 [ps]

Seed laser duration (FWHM) = 150 fs

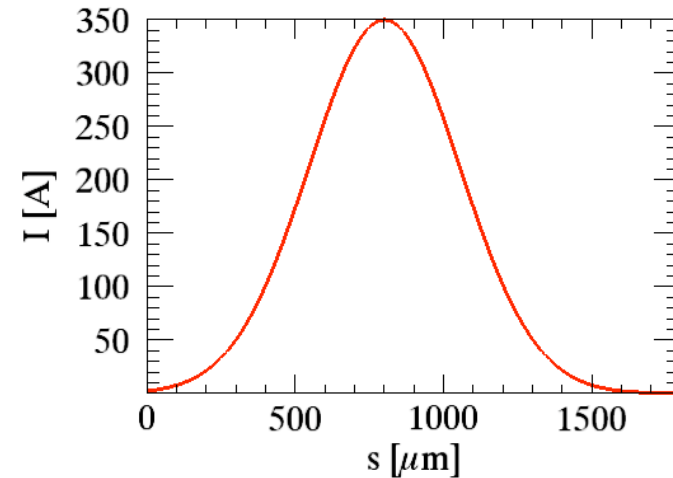
Peak power = 1 - 100 [MW]

Input radius = 320 [ $\mu\text{m}$ ]

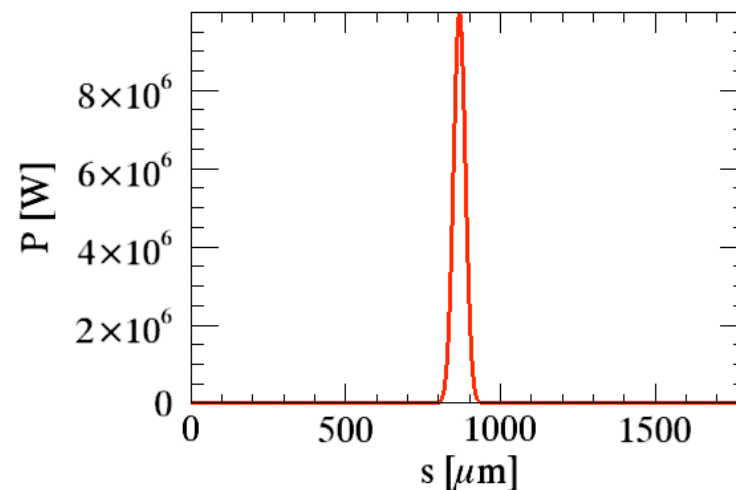
Central wavelength = 788 [nm]

Spectral width (FWHM) = 7 nm

E-beam current



Seed Laser



# GENESIS calculation for SDL setup

## e-beam

- energy = 102 MeV
- duration = 1.9 ps (fwhm)
- peak current = 300 A
- distribution = Gaussian
- emittance = 3 mm.mrad

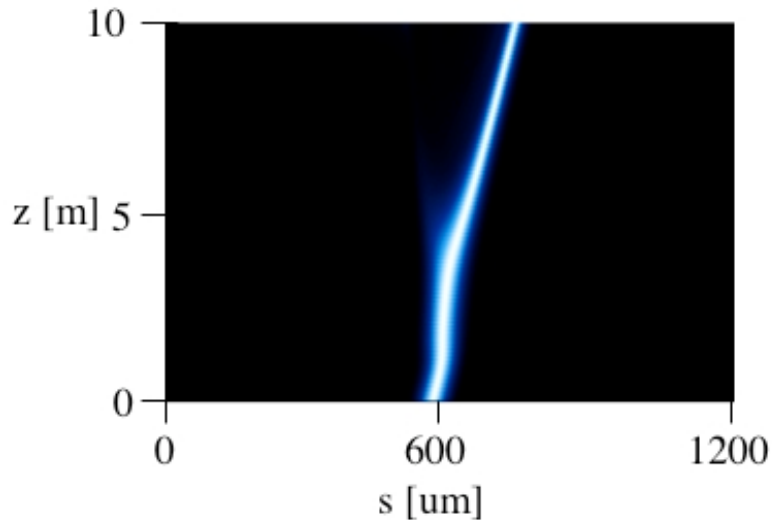
## Seed laser

- wavelength = 790 nm
- duration : 150 fs (fwhm)
- peak power = 1 MW
- distribution = Gaussian

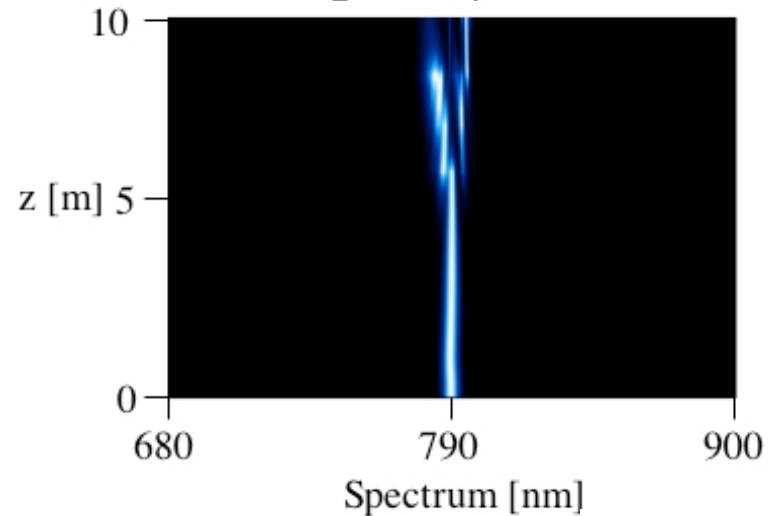
## NISUS undulator

- K = 1.1
- period = 3.89 cm
- # periods = 256
- total length = 10 m

### Time domain

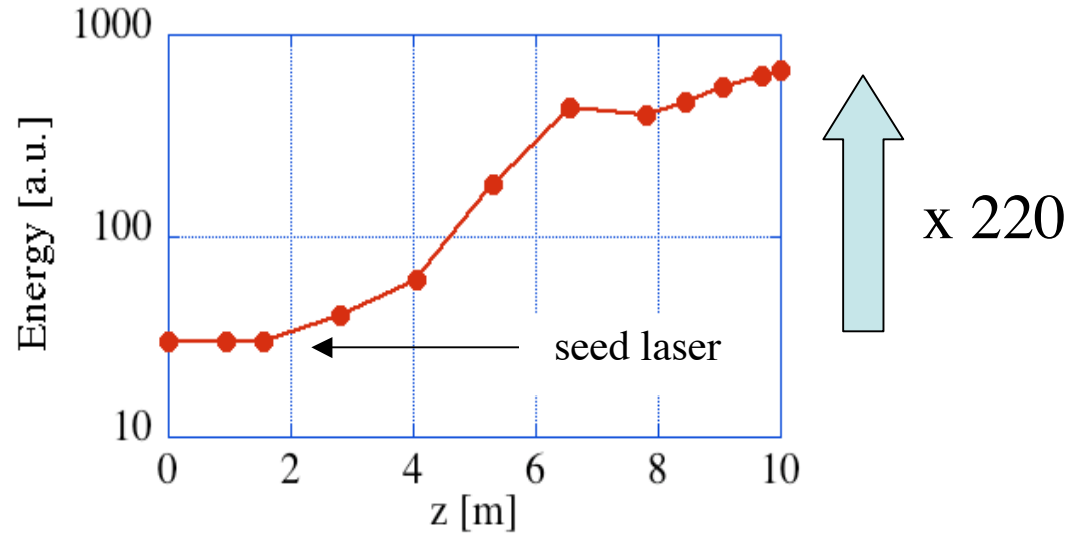


### Frequency domain

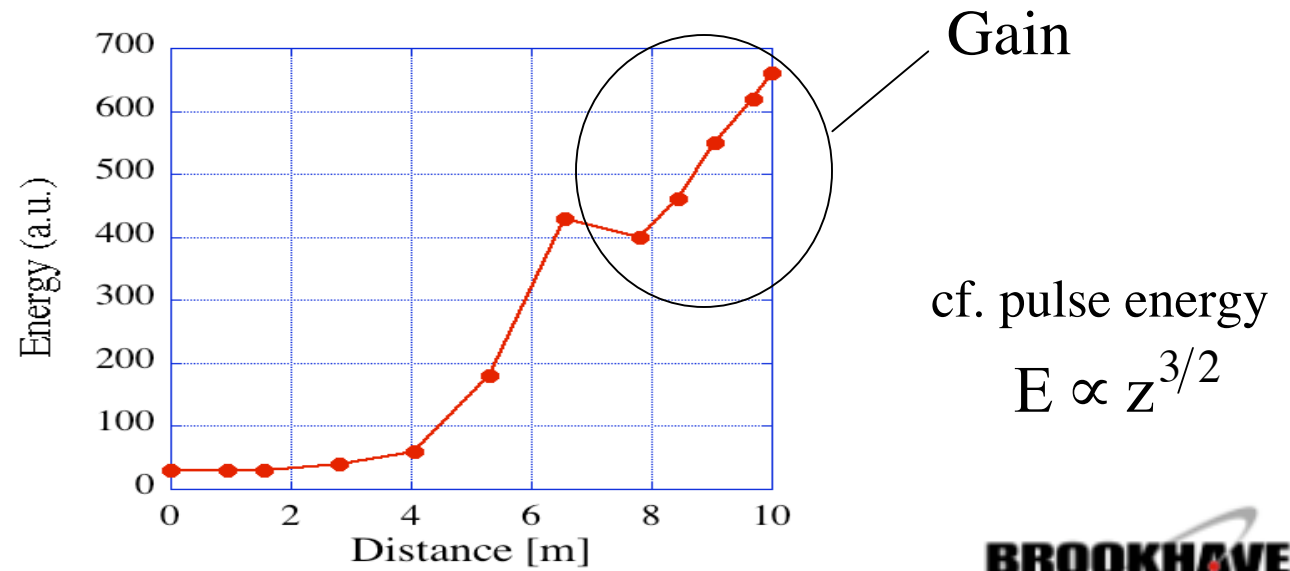


# FEL gain measurement

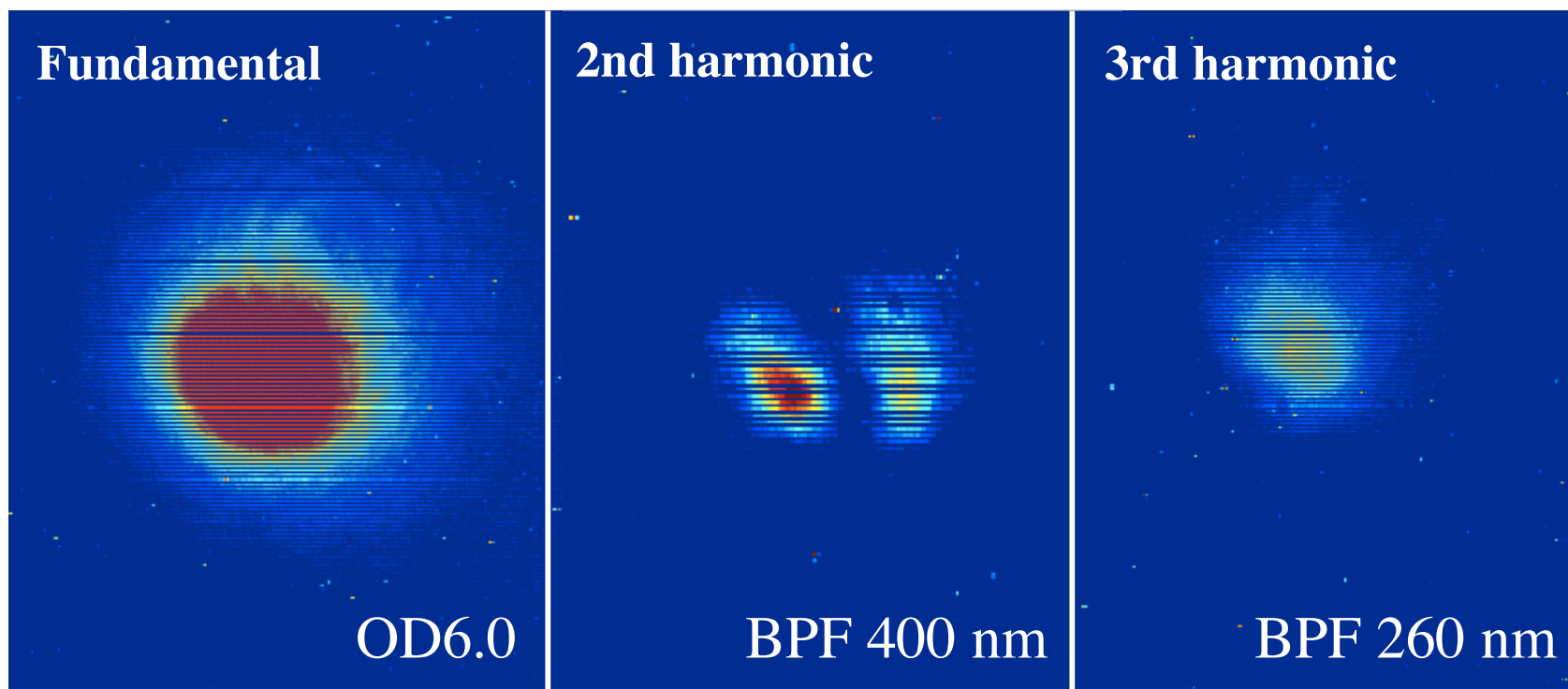
Log scale



Linear scale



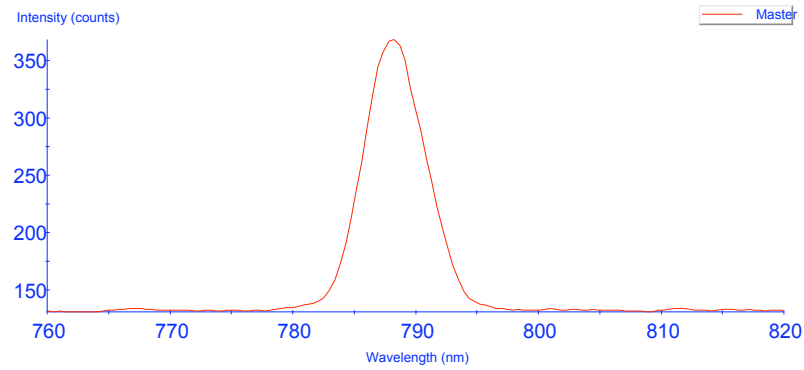
# Spatial distribution



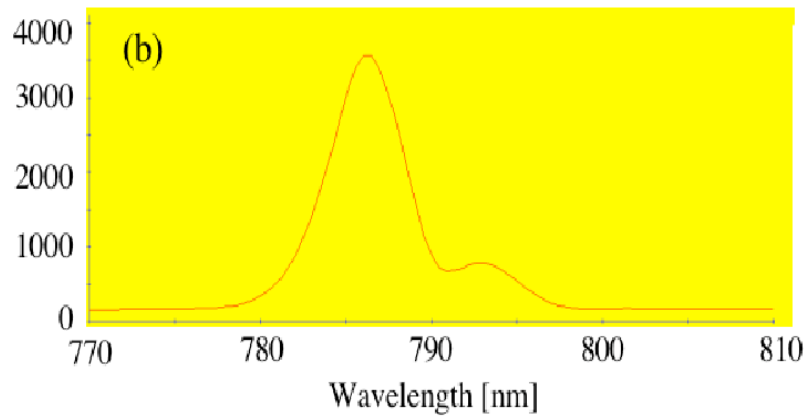
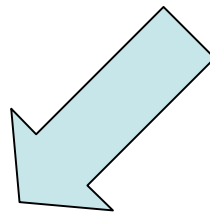


# Spectrum

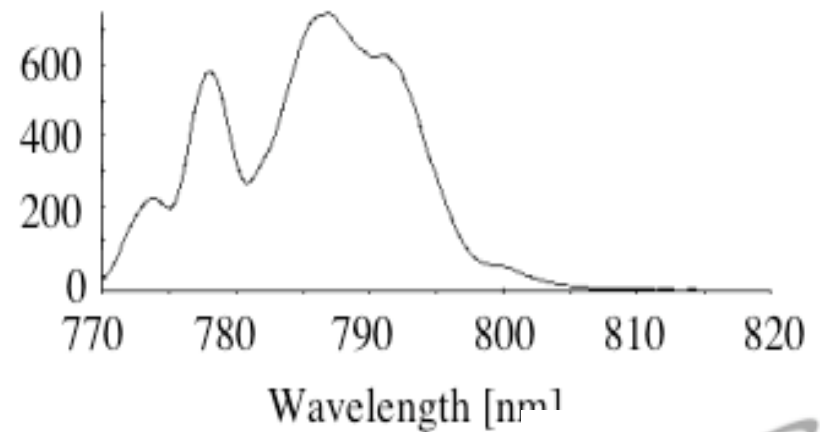
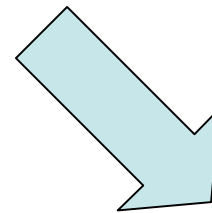
Seed laser



Seed laser : 4.5 ps

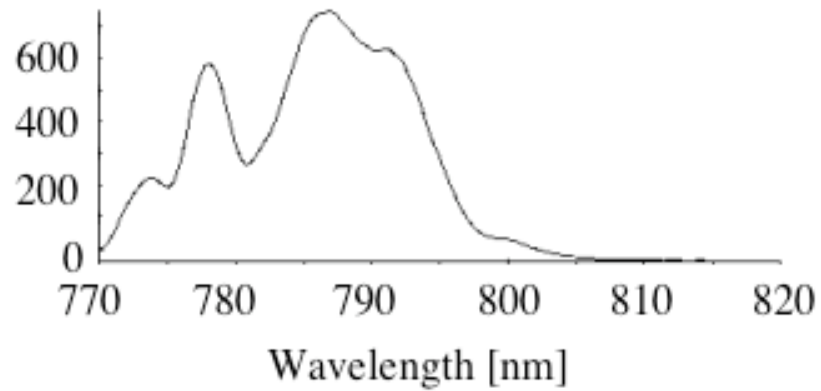


Seed laser : 100 fs



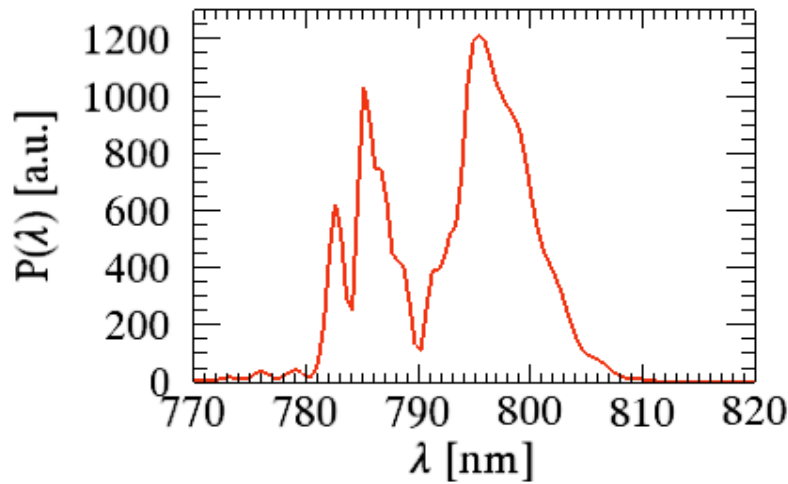
# Spectrum at the end of NISUS undulator

Experiment

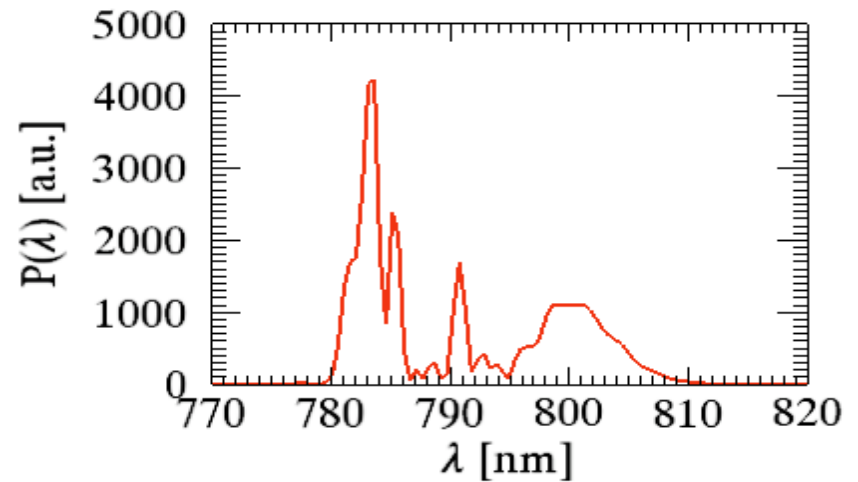


GENESIS calculation

8 m

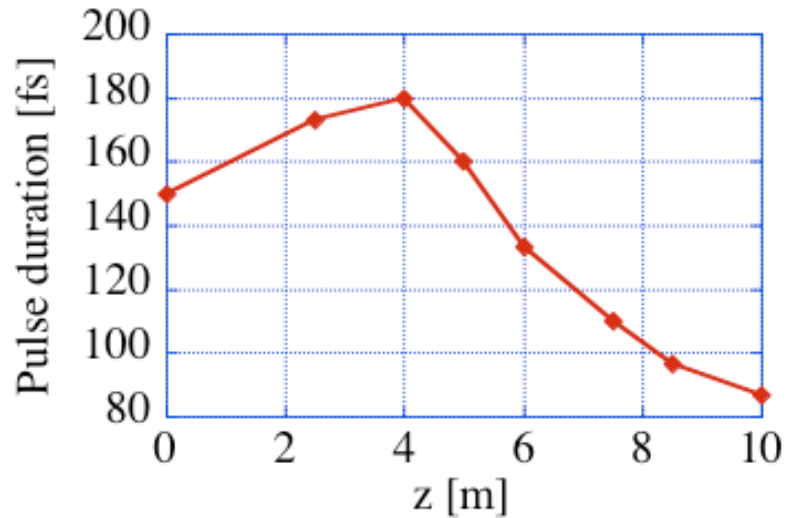


10 m

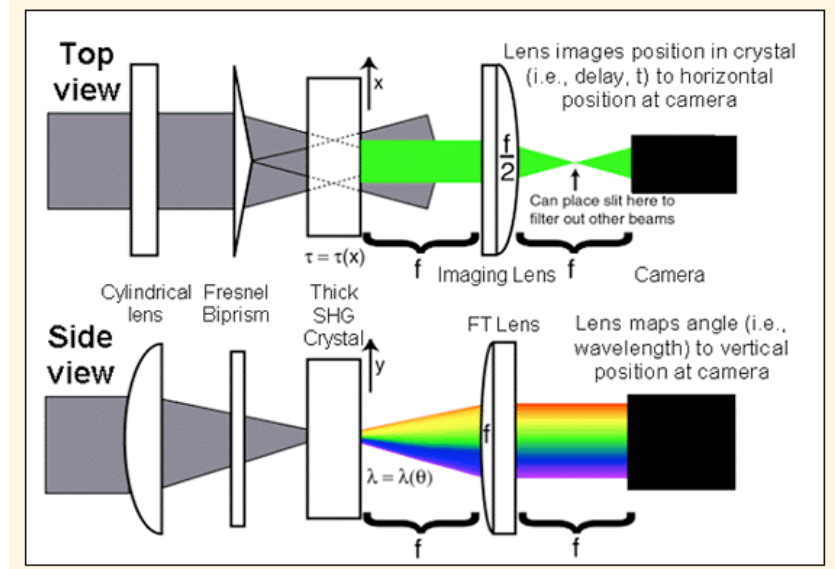


# Nonlinear evolution

Nonlinear evolution  
by GENESIS



## GRENUILLE (SHG-FROG)



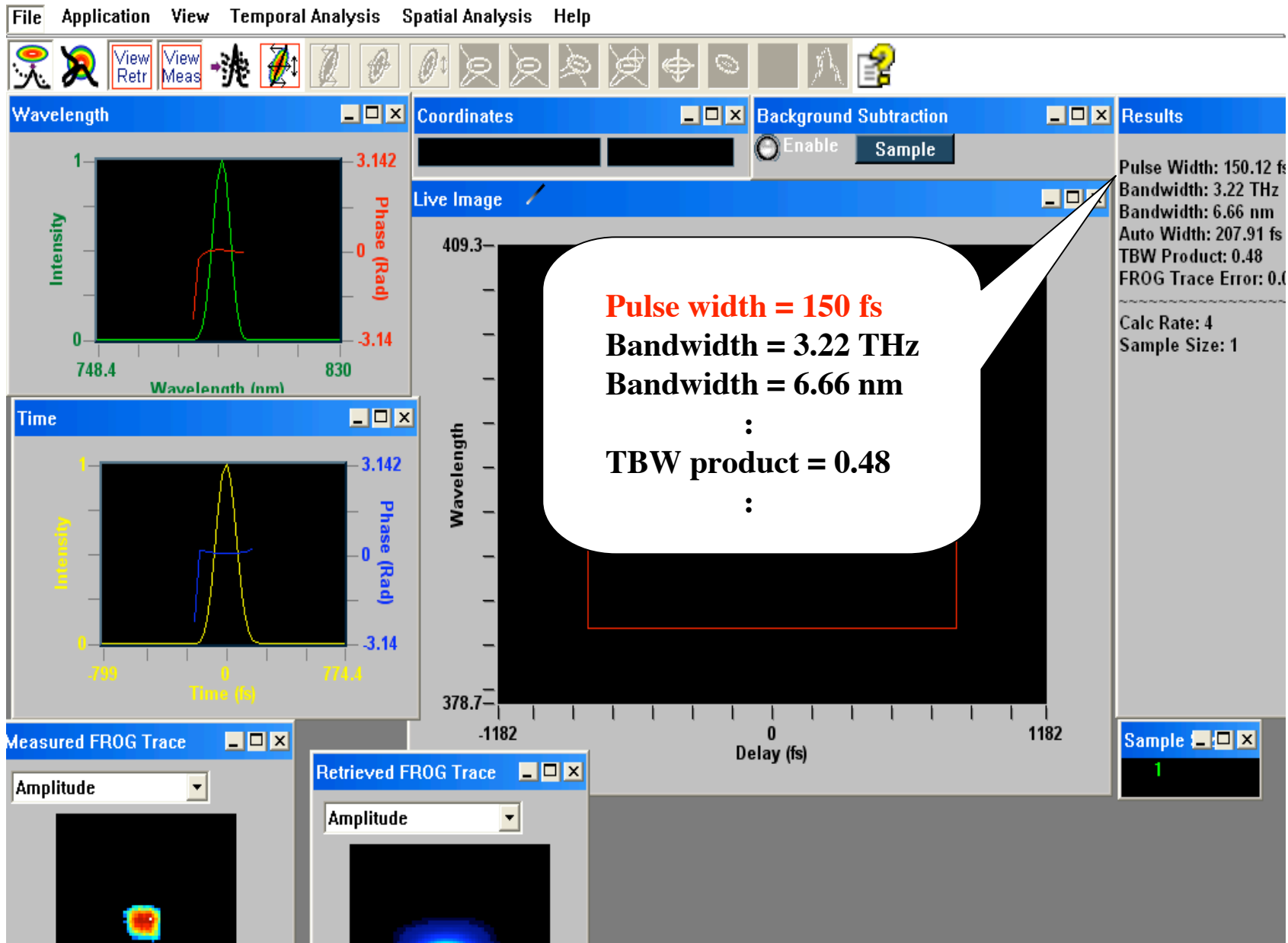
[www.swampoptics.com/](http://www.swampoptics.com/)

cf. FEL measurement by FROG

Richman et al., Opt. Lett., 22, 721 (1997).

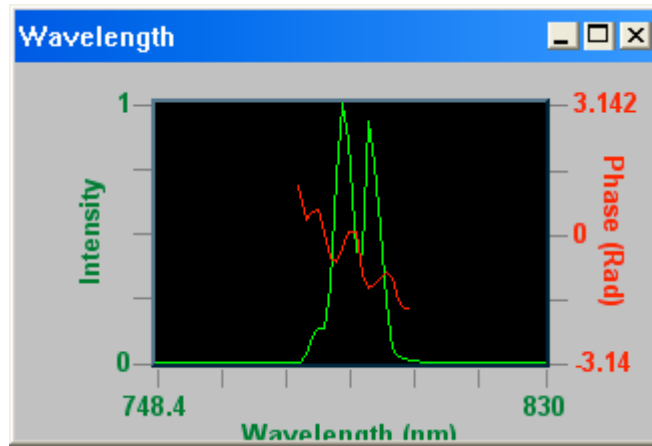
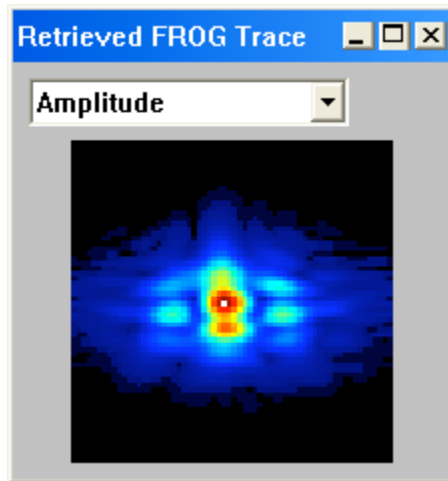
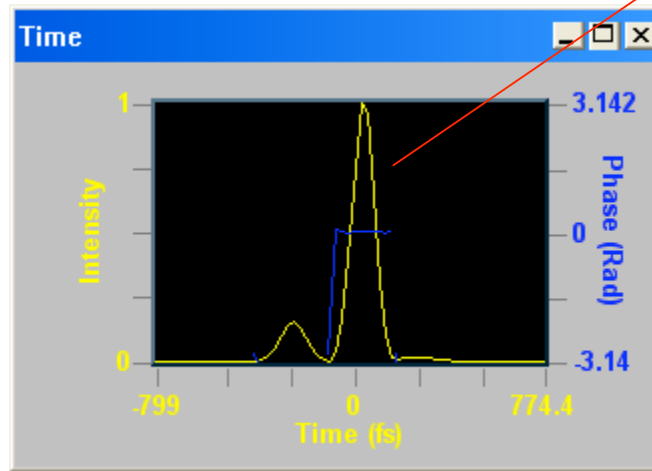
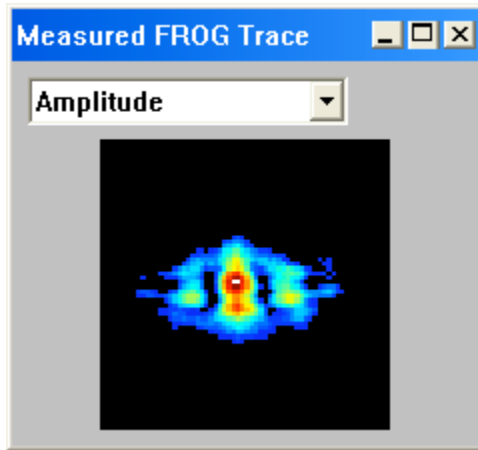
Y. Li, et al, PRL 89 (2002) 234801.

# FROG measurement

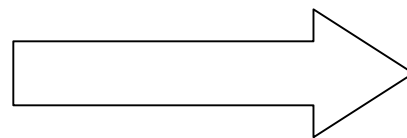


# Nonlinear evolution

self-similar solution by Bonifacio

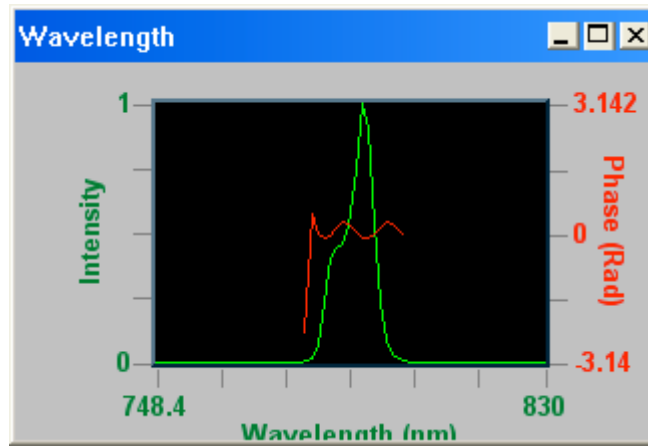
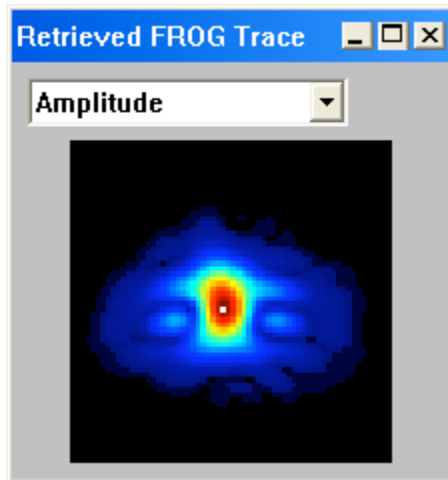
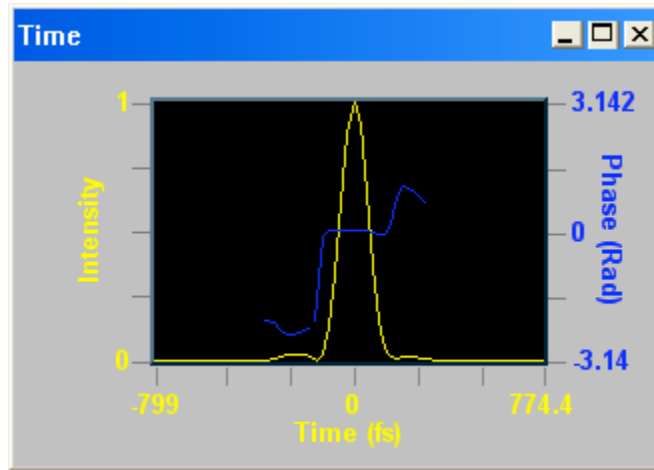
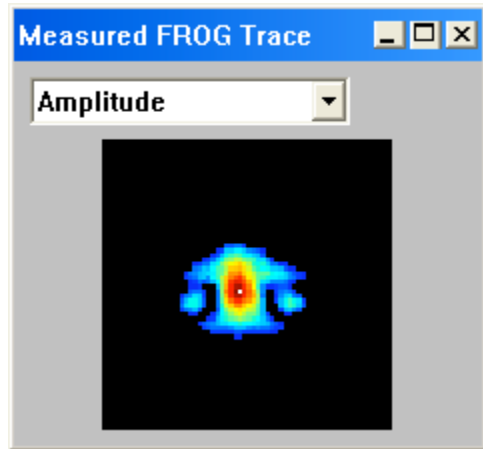


Seed laser  
150 fs

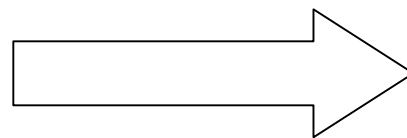


Seeded FEL  
104 fs

# Nonlinear evolution

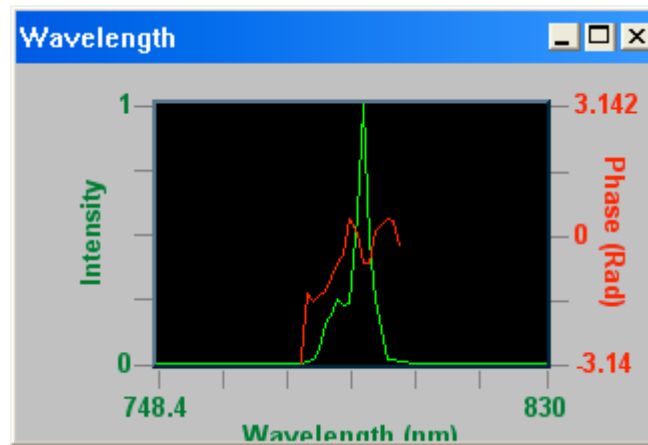
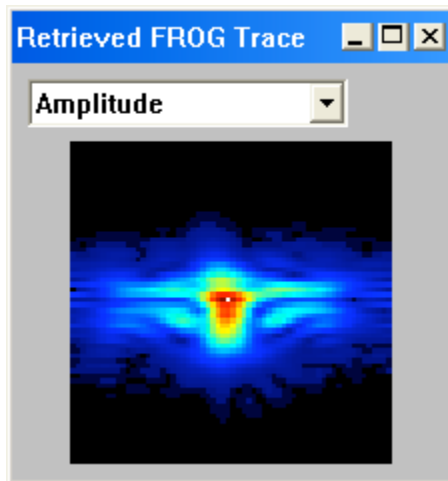
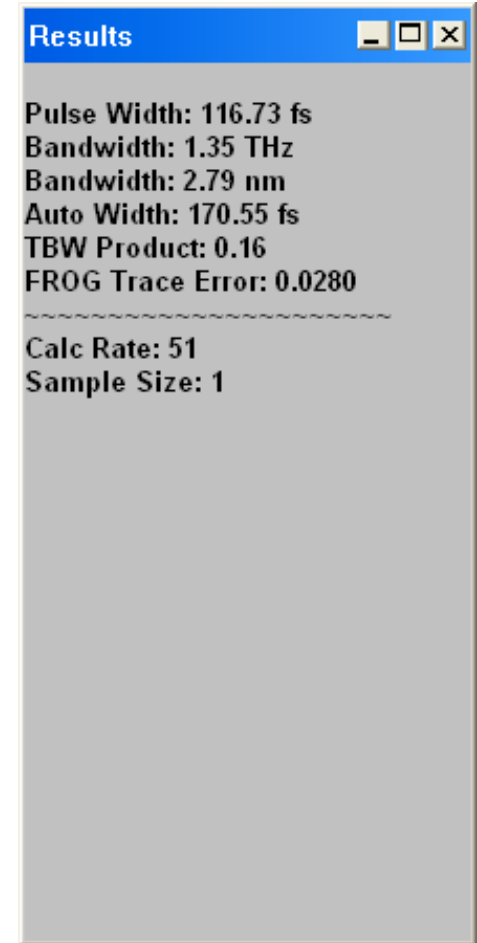
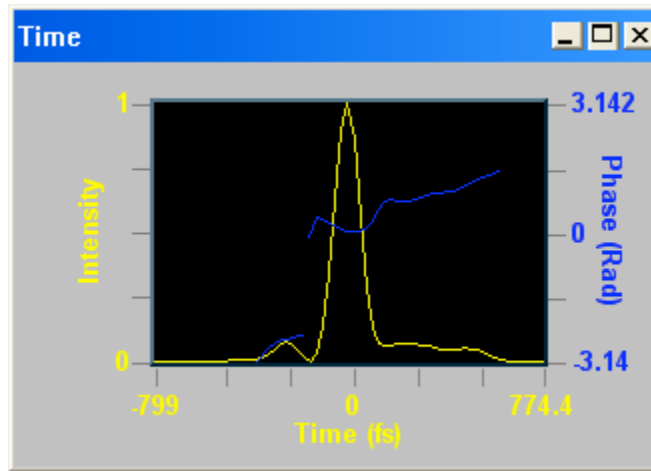
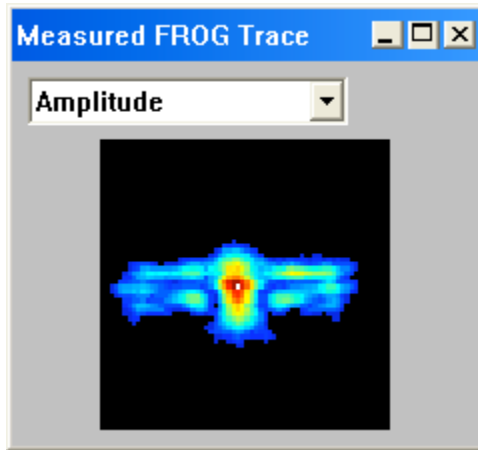


Seed laser  
150 fs

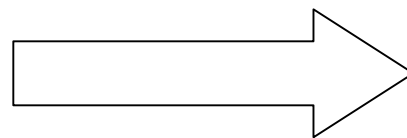


Seeded FEL  
123 fs

# Nonlinear evolution

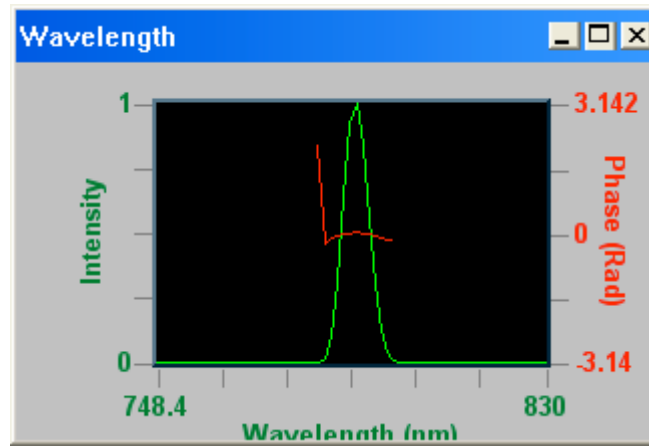
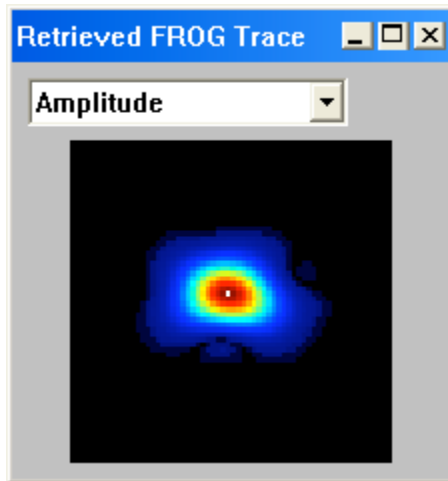
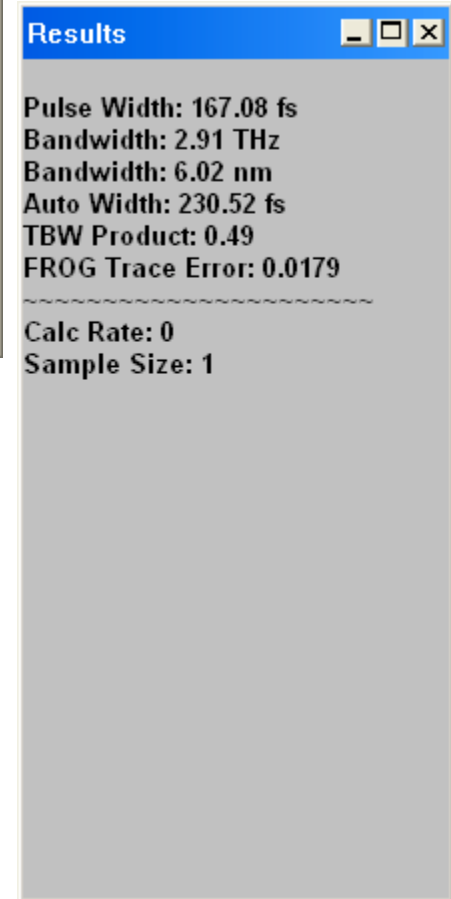
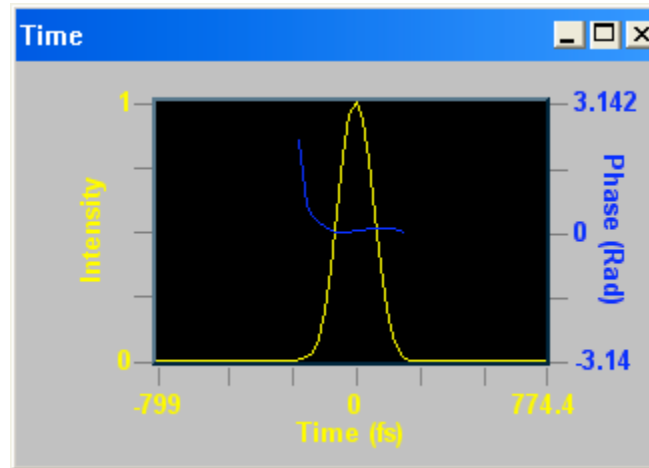
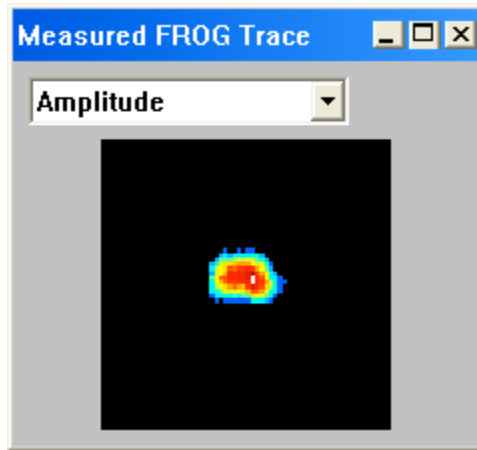


Seed laser  
150 fs

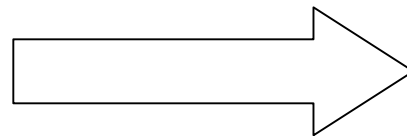


Seeded FEL  
117 fs

# Jitter effect



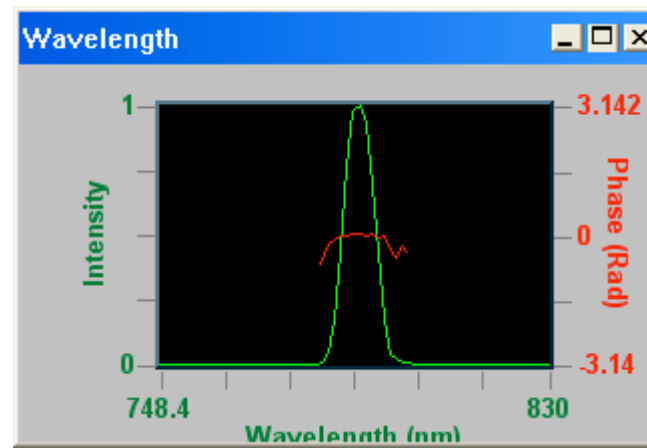
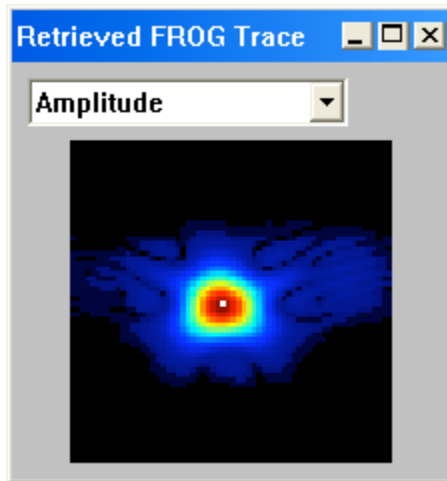
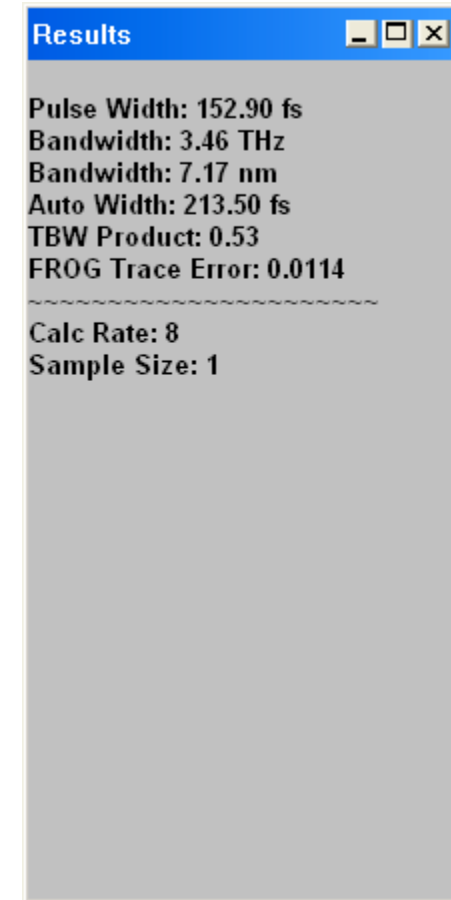
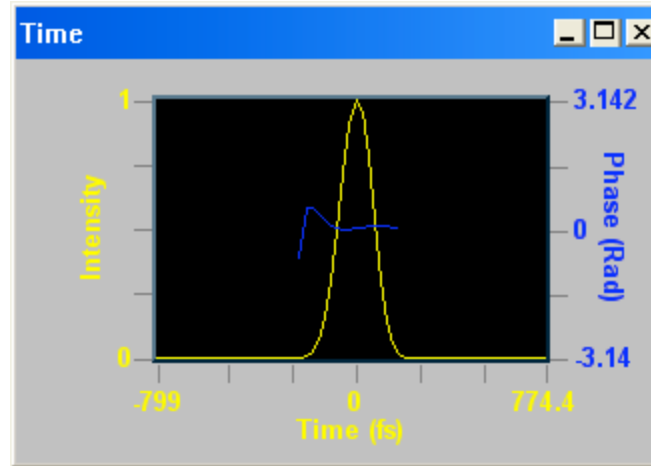
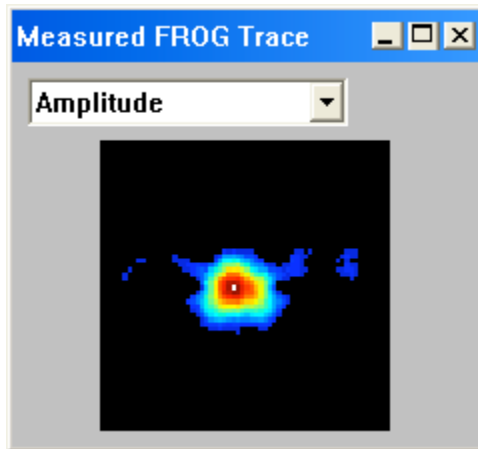
Seed laser  
150 fs



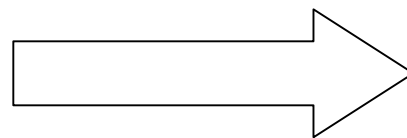
Seeded FEL  
167 fs



# Jitter effect

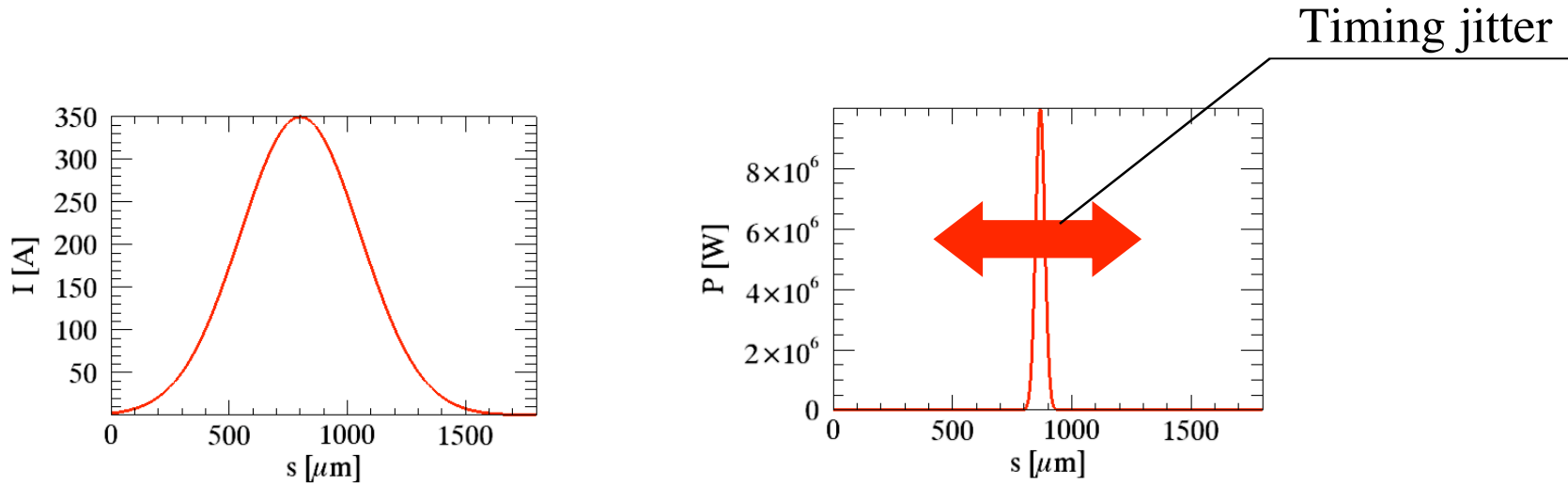


Seed laser  
150 fs

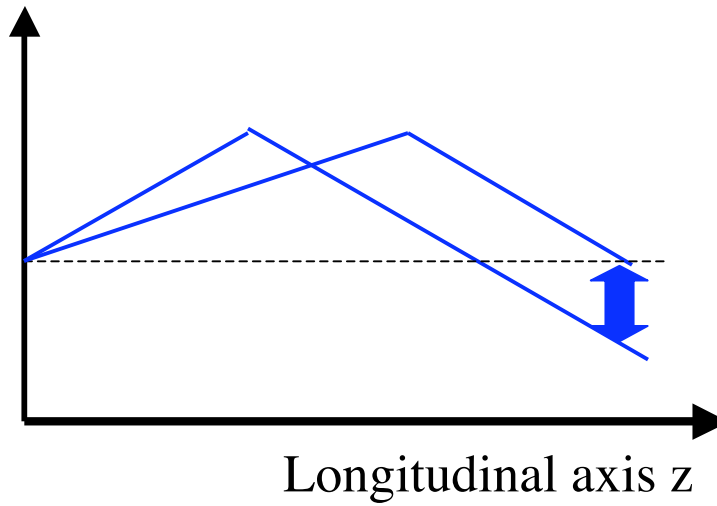


Seeded FEL  
153 fs

# Shot-to-shot fluctuation



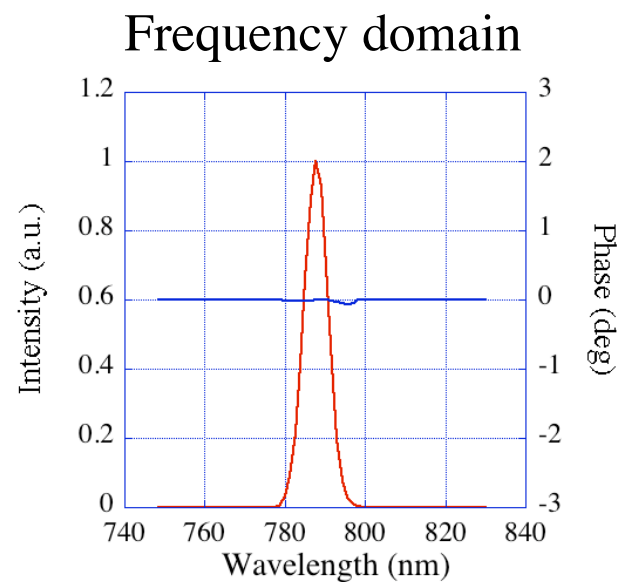
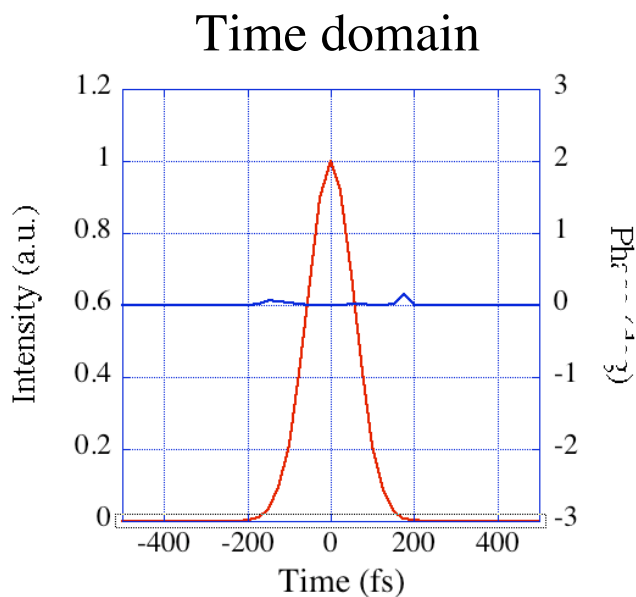
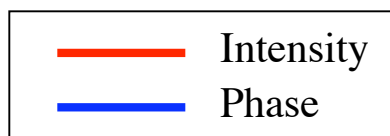
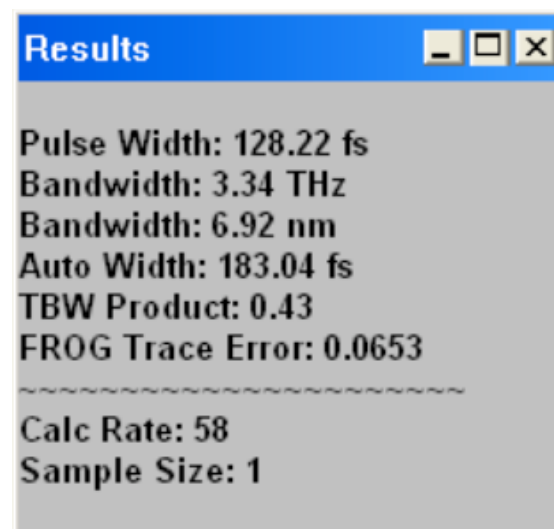
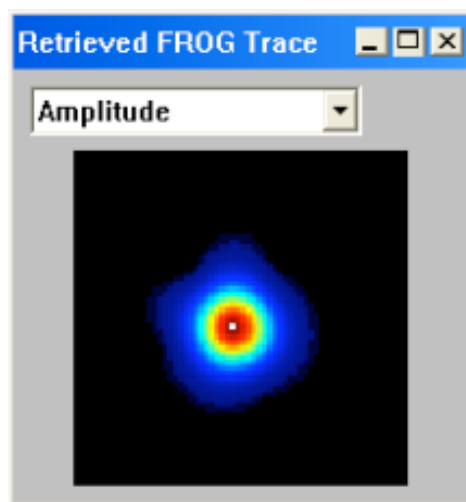
Pulse duration



# FROG measurement - seed laser -

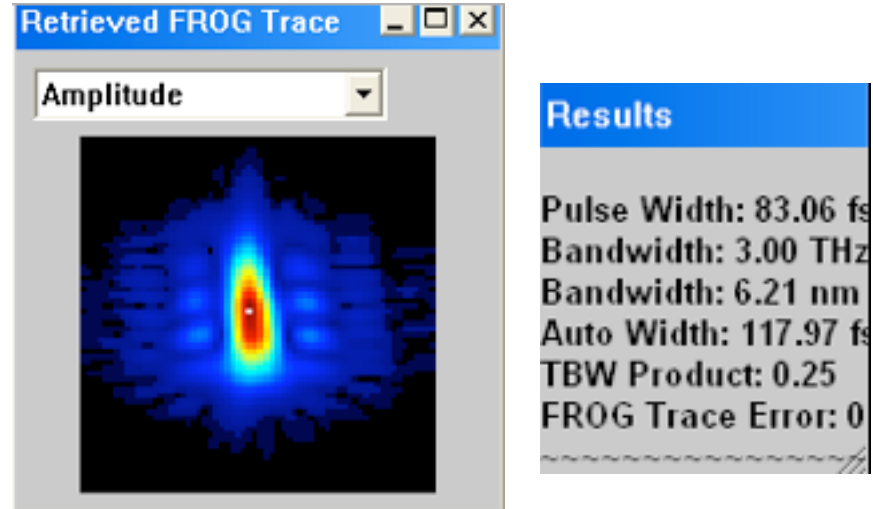
Seed laser

150 fs  $\longrightarrow$  130 fs

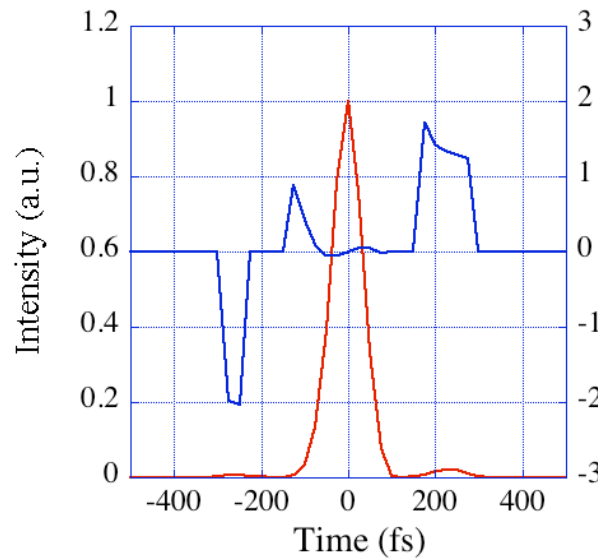


# FROG measurement

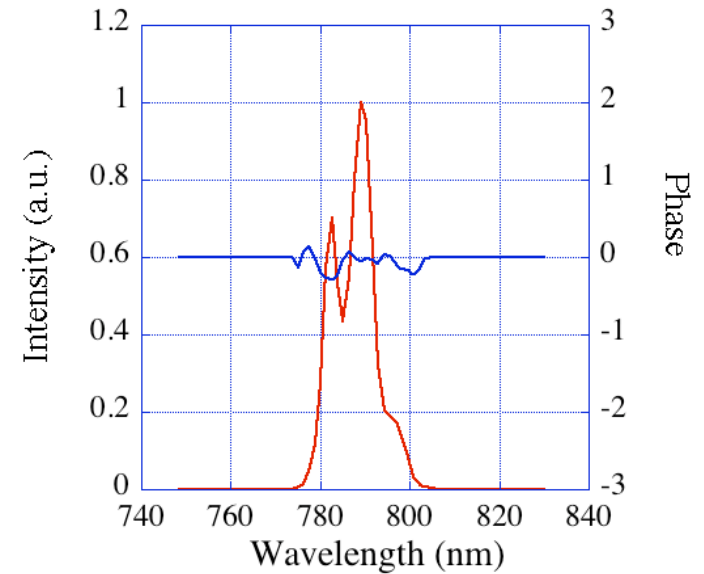
FEL light  
Pulse duration (fwhm)  
83 fs



Time domain



Frequency domain



— Intensity  
— Phase

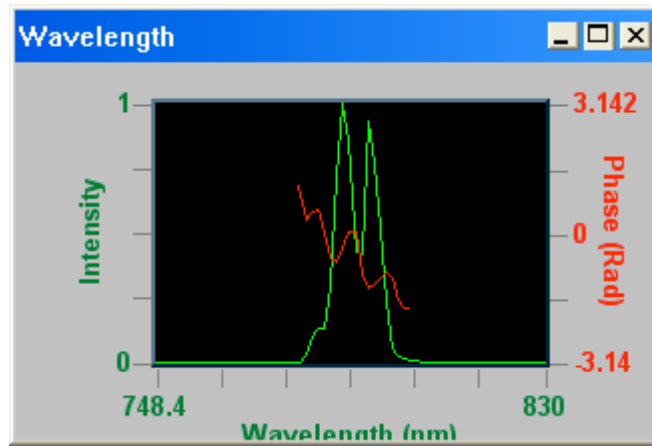
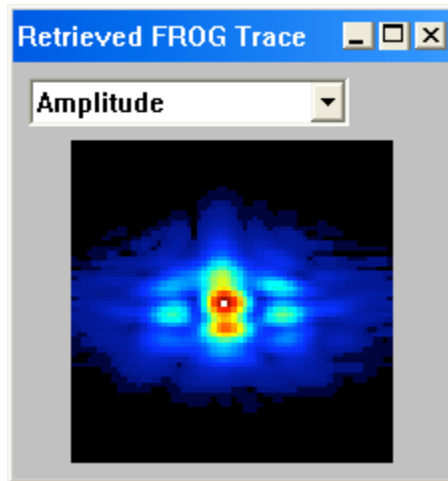
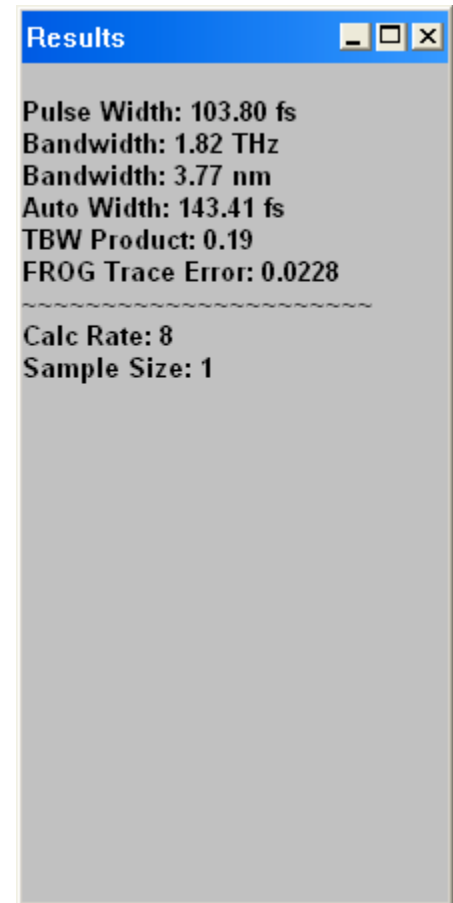
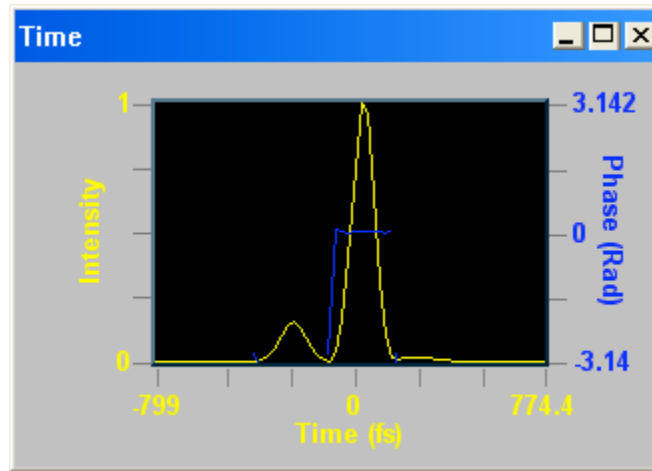
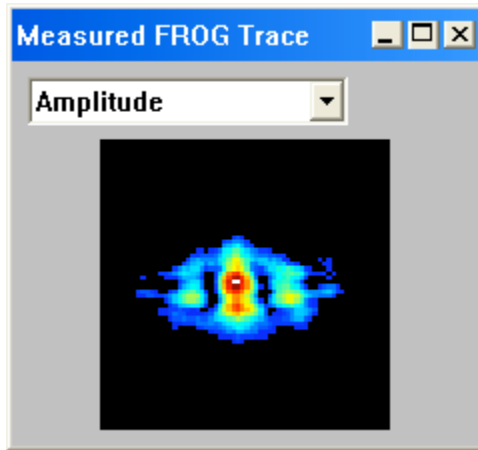
## Conclusion

Superradiance in a single-pass seeded FEL was demonstrated.

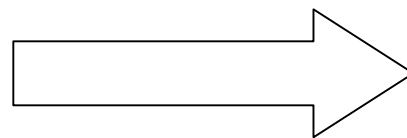
- Nonlinear gain after saturation observed.
- Spatial distributions of higher harmonics observed.
- Wide-band multi-peak FEL spectrum obtained.  
Agreed well with GENESIS calculation.
- Pulse shortening from 150 fs to 100 fs, and 130 fs to 80 fs observed.

\* Stability has not been well analyzed.

# Nonlinear evolution

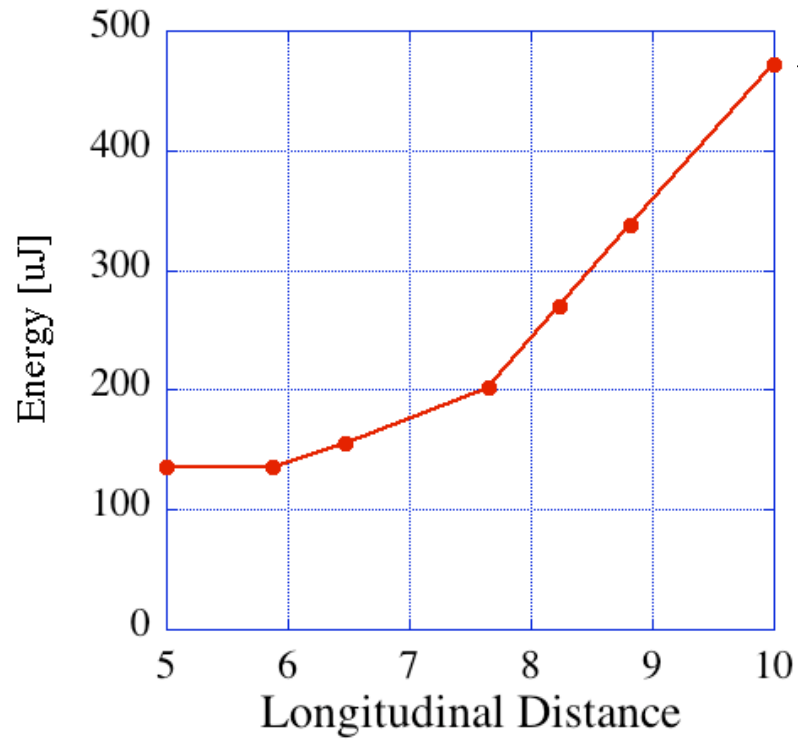


Seed laser  
150 fs



Seeded FEL  
104 fs

# Gain Curve



Peak power  
~5 GW\*

\* will be calibrated precisely.