The VISA II Experiment

A study in electron beam dynamics and high gain, ultra short pulses in SASE FEL.

Gerard Andonian
UCLA
PBPL Seminar Series
July 21, 2004

Some Acronyms

Definitions of some of the terms used throughout this talk.

- VISA : Visible to Infrared SASE Amplifier
- SASE: Self Amplified Spontaneous Emission
- FEL : Free Electron Laser

Experiment Outline

- VISA I
- Re-commissioning FEL
  - High Bandwidth Regime (“VISA IB”)
  - Double Differential Spectrum
- VISA II
  - Chirped beam short pulses
    - Sextupoles
  - Grenouille
- Compressor

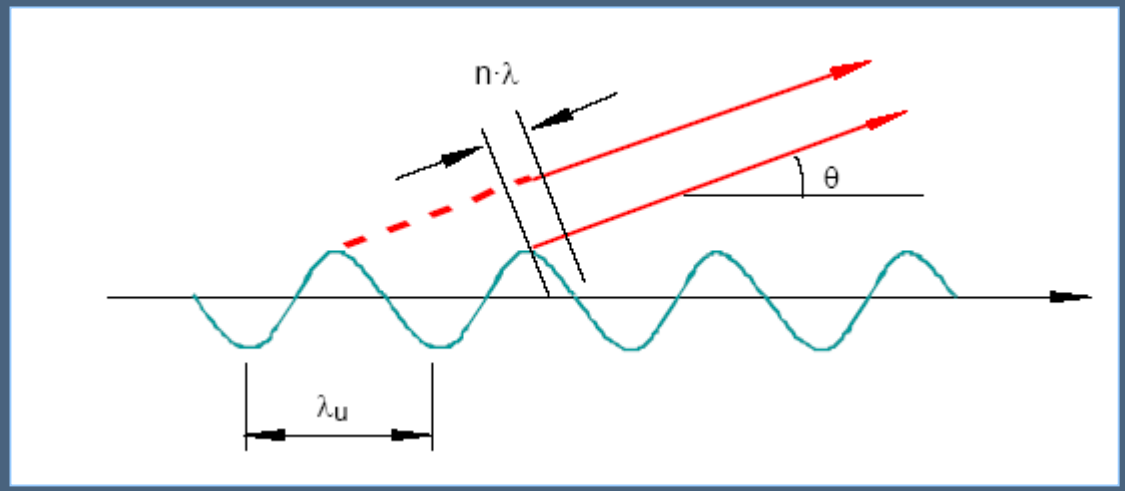
Global Details

- Collaborators
  - UCLA, INFN-LNF, ENEA-Frascati, INFN-Milano, BNL
- Support
  - ONR, DoE BES, DoE HEP, INFN, NSF
- Notable Publications from VISA I
  - A. Tremaine, et al., “Experimental Characterization of Nonlinear Harmonic Radiation from a Visible Self-Amplified Spontaneous Emission Free-electron Laser at Saturation”, Physical Review Letters, 88, 204801 (2002)
  - A. Murokh, et al., “Properties of the ultrashort gain length, self-amplified spontaneous emission free-electron laser in the linear regime and saturation”, Phys. Rev. E 67, 066501 (2003); also published in July 2003 issue of Virtual Journal of Ultrafast Science http://www.vjultrafast.org
  - A. Tremaine, et al., “Fundamental and harmonic microbunching in a high gain self-amplified spontaneous emission free electron laser”, Phys. Rev. E 66,036503 (2002)

FEL Basics

- FEL converts K.E. of a relativistic e-beam to coherent EM radiation
- Components of a Free Electron Laser
  - Electron beam: The lasing medium
  - Undulator: The effective potential
  - Radiation Field: The seed
    - External seed or initial spontaneous radiation

FEL: Resonance



- Resonance Condition
  - after one undulator period the radiation field advances one wavelength to be in resonance with electron

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

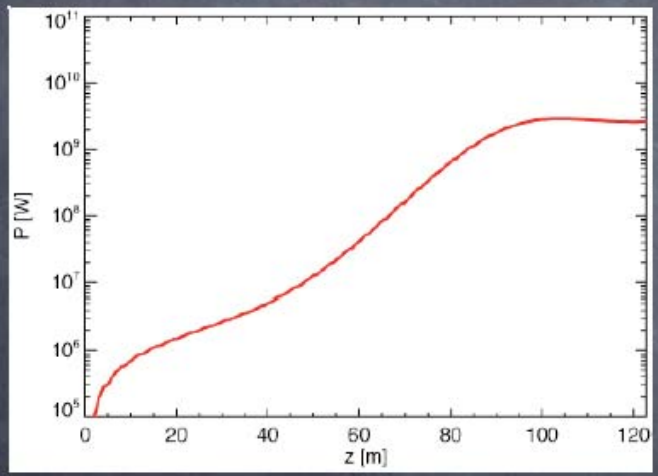
FEL: Applications

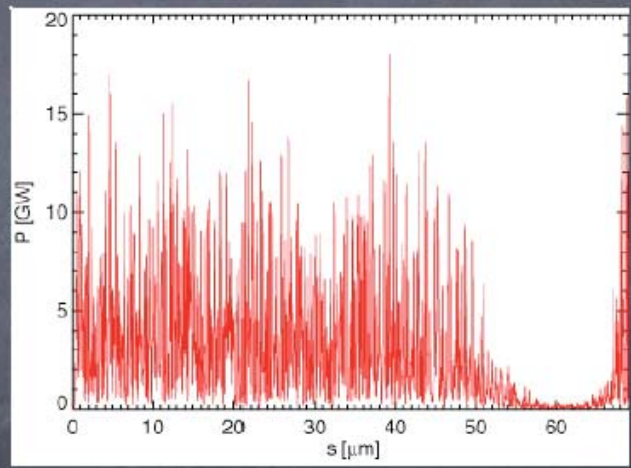
- FEL is tunable over a wide range
  - Example : LCLS, TESLA
    - short wavelength (angstrom)
    - pulse duration ~ 10 fs
    - output power ~ 10 GW
- Probe for Atomic Structural Dynamics
  - time scale of atomic vibration~ 100 fs
    - chem. reactions, surface processes
  - need x-ray (high brightness) to study

LCLS

Example: LCLS

- LCLS: E=14.1 GeV, λu=3cm, K=3.7, λ=1.5 Å

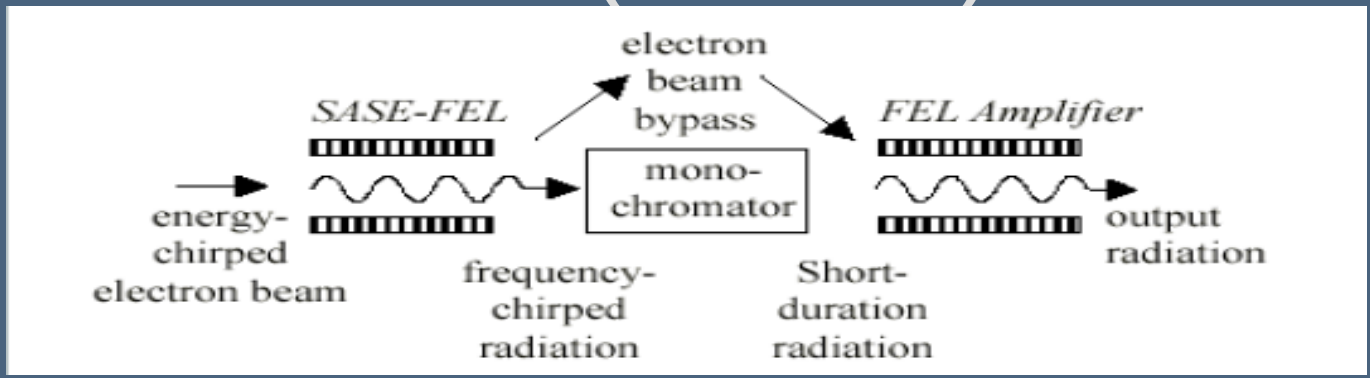




S. Reiche, "Free Electron Lasers", Physics 250 Fall 2003, UCLA, Lecture 8

- LCLS
  - user facility (multi institutional collaboration)
  - 100m undulator, 1 km linac
- Shift in research
  - from proof-of-principle to enhancement of radiated output (~10 fs, x-ray)

Motivation for chirped beam FEL (VISA II)



- Proposed Scheme for ultra short pulses
  - Energy chirped e-beam ➔FEL➔ freq. chirped radiation
- Explore Limits of SASE FEL with energy chirped e-beam
- Develop advanced beam manipulation & measurements

Energy chirped e-beam

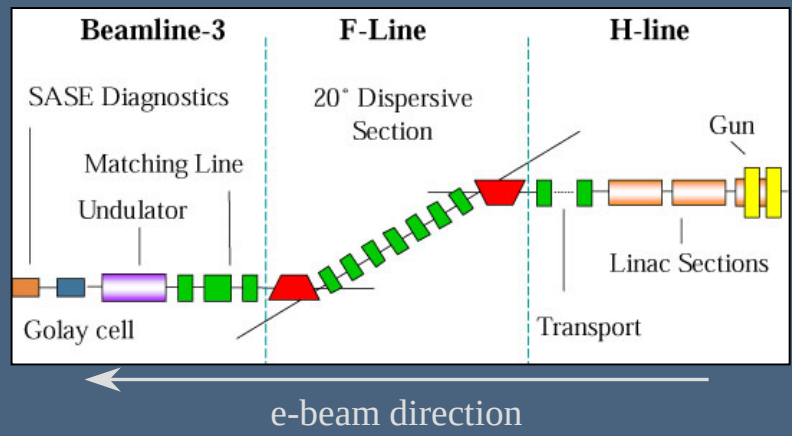
$$\frac{\delta\gamma}{\gamma} = \alpha\frac{l}{L_b}$$

Freq. chirped radiation output

$$\frac{\delta\omega}{\omega} \simeq 2\frac{\delta\gamma}{\gamma} = 2\alpha\frac{l}{L_b}$$

ATF & VISA Undulator

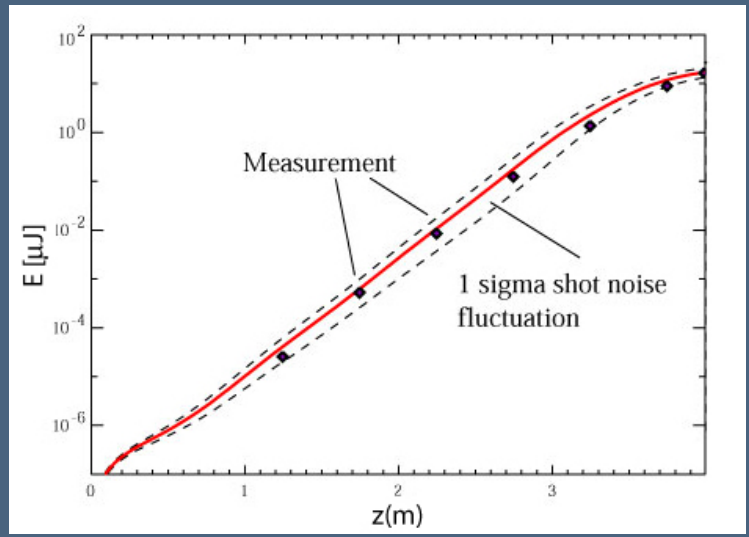
- Accelerator Test Facility (ATF) at BNL
  - Host for VISA I & II
  - 71 MeV beam
  - 28 m beam transport
    - 20 deg bend (F-line)
- Undulator
  - 4 x 1m sections
  - FODO lattice superimposed (25 cm period) –strong focusing
  - External steering coils (8)
  - Intra-undulator diagnostics
    - 50 cm apart
    - double-sided silicon
    - SASE FEL
    - e-beam (OTR)



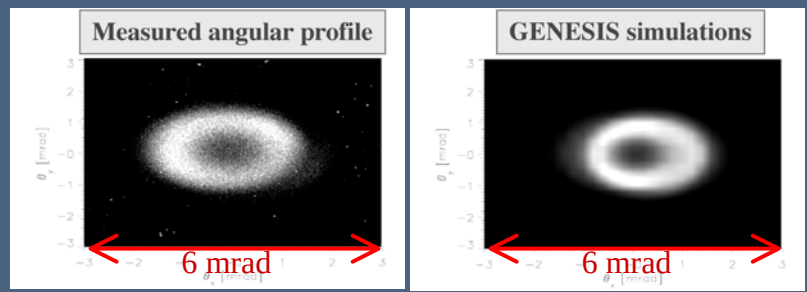
VISA Undulator Parameters	
Undulator type	Planar (NdFeB)
Number of periods (N_u)	220
Peak field (B_{pk})	.75 T
Undulator Period (λ_u)	1.8 cm
Gap (g)	6 mm
Undulator Parameter (K)	1.26

VISA I Summary

- Results
  - Gain ~ 10^8 due to nonlinear compression in dog-leg (F-line)
  - Shortest gain length recorded (~ 18 cm)
  - Higher order angular spectra
  - CTR & Higher Harmonic Gain
- Start to End Simulation Suite
  - UCLA Parmela
  - Elegant
  - Genesis
- Codes Benchmarked to measurements
  - Post linac, post-dogleg, FEL



VISA I Gain Curve



Far-field radiation pattern (angular spectrum): measured (left), simulation (right)

A Stepping Stone: “VISA IB”

What is “VISA IB”?

A stand-alone, transitional experiment, running under similar operating conditions, yielding interesting results and some unexplained behavior.

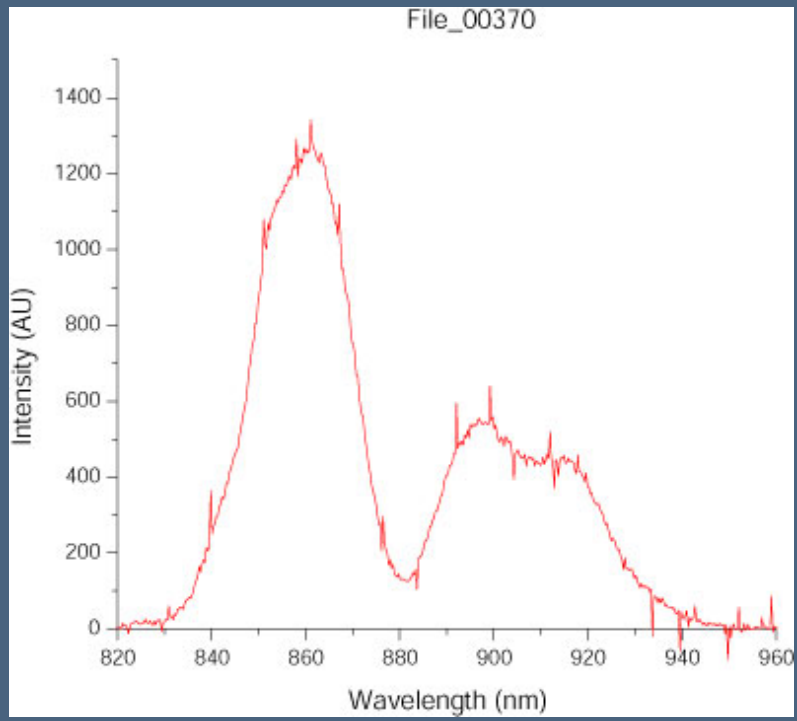
Outside Undulator Box with FEL Optical Transport Line

GOALS & Accomplishments

- Re-commission FEL
- Modify beamline hardware
- Run e-beam with high chirp
  - High Bandwidth Regime FEL
- Develop new diagnostics
  - Double Differential Spectrum (DDS)
- STE Simulation Studies & Improvements
  - FEL
  - Phase Space correlations (e-beam)

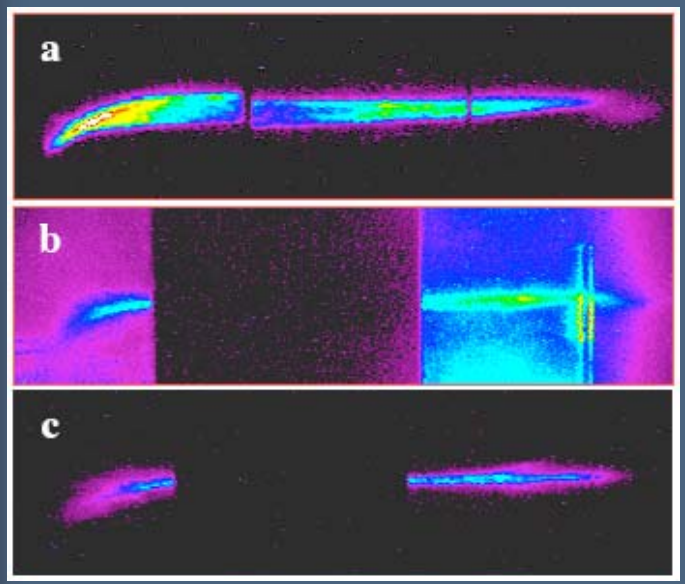
VISA IB: Large Bandwidth
(Chirped Beam Amplification)

- High gain FEL
  - SASE energy ~2 μJ
  - close to saturation
- 11% total bandwidth observed
- Very reproducible and unusually stable
  - insensitive to RF drifts and phase jitter
- Characteristic double-spike structure
- Parasitic Mode!



Wavelength Spectrum of FEL at VISA measured with Ocean Optics USB2000 Spectrometer.

VISA IB: Chirping the beam



e-beam at HES

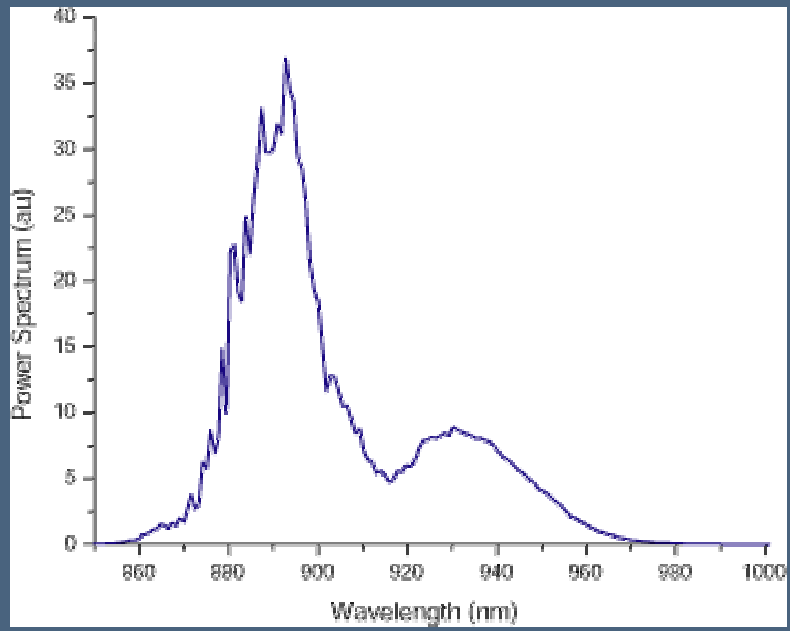
a) fully closed slits (500 pC, 2.8% chirp)
b) fully open slits (60 % Transmission, 330pC)
c) compressed fraction of beam (1.5% chirp)

- High energy slits (HES)
  - adjustable collimator
  - Controls beam size in F-line
- FEL stability
  - same fraction of beam propagates through HES,
  - regardless of centroid jitter
- Compression
  - monitored by Golay cell
    - measures CTR
    - CTR peaked when p_0 set to optimize compression
  - Current ~ 300A
    - better than VISA I
  - Compression stronger
    - higher degree of chirp

VISA IB: STE - Spectrum

- Genesis Results
  - Experimental Spectrum features reproduced
  - Numerical Studies on no energy spread yield similar results
  - Angles Important
    - Off-axis Doppler Shift

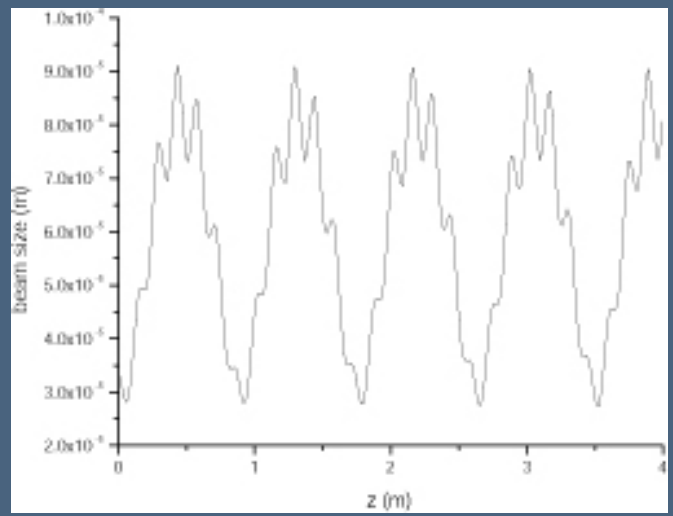
$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{1}{2}K^2+(\gamma\theta)^2\right)$$



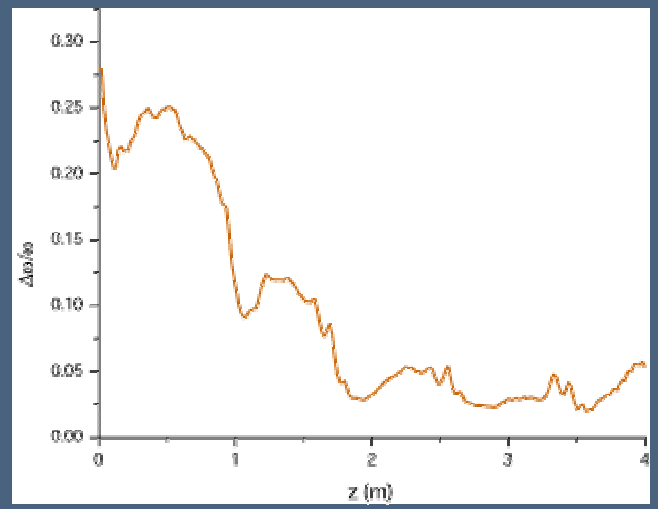
FEL output Spectrum reproduced by Genesis (~10% bandwidth)

VISA IB: STE - FEL

- e-beam size
  - transverse beam size



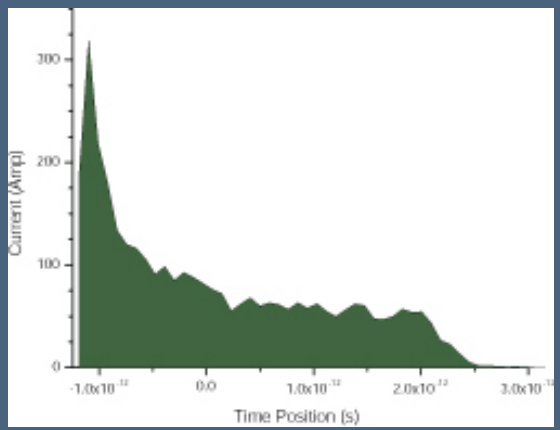
- Bandwidth Evolution
  - Nonlinear momentum dispersion errors
  - Transverse injection errors (steering)
  - large betatron offset (200 μm offset)
  - Parasitic off-axis gain



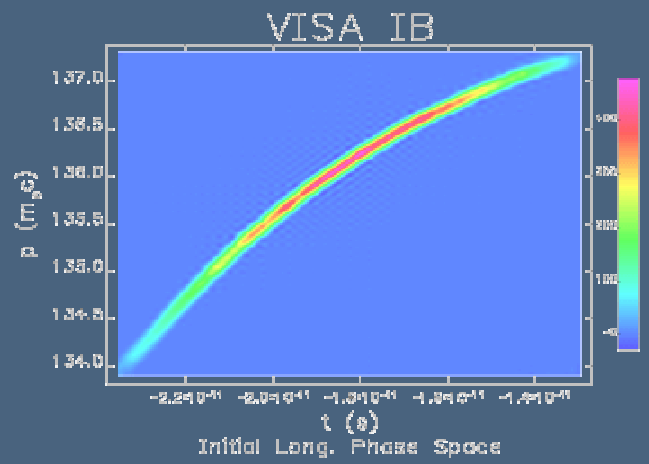
Undulator Position

VISA IB: STE - Compression

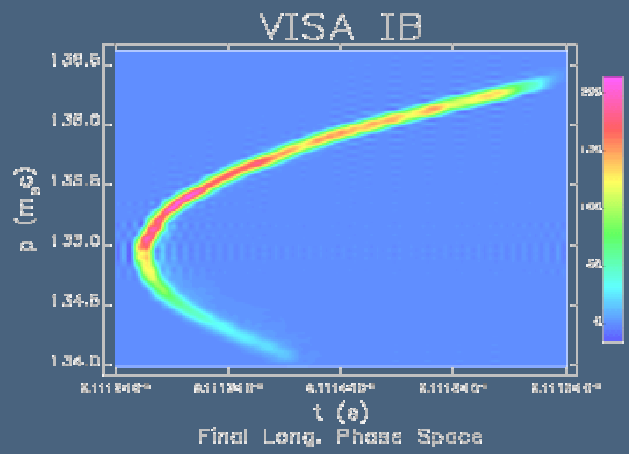
- Linear chirp applied at linac
- Compression in dogleg
  - Portion of beam is always in “correct” comp. regime
  - Collimation ~40% (300 pC)
  - Benchmarked to data taken in F-line
- Very high current
  - Peak current ~300 Amp
  - Lasing Peak < 50 fs



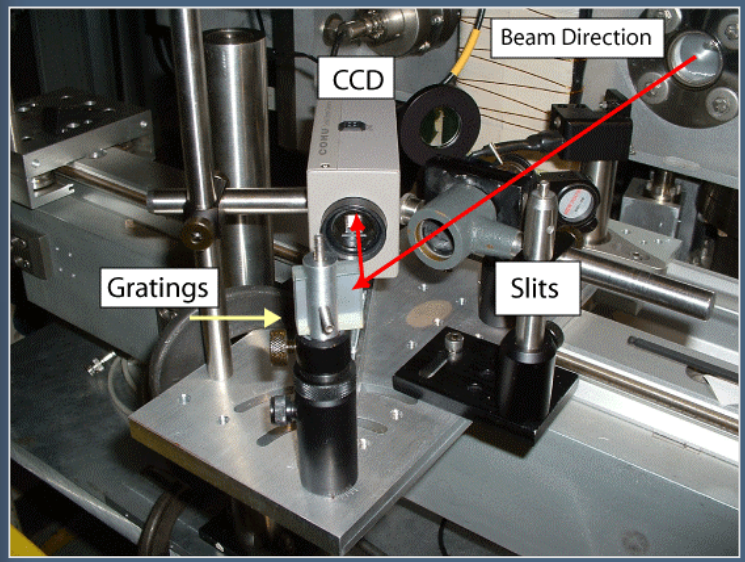
Current dist. prior to injection



Long. Phase Space after linac(top) and before injection (bottom)[elegant].



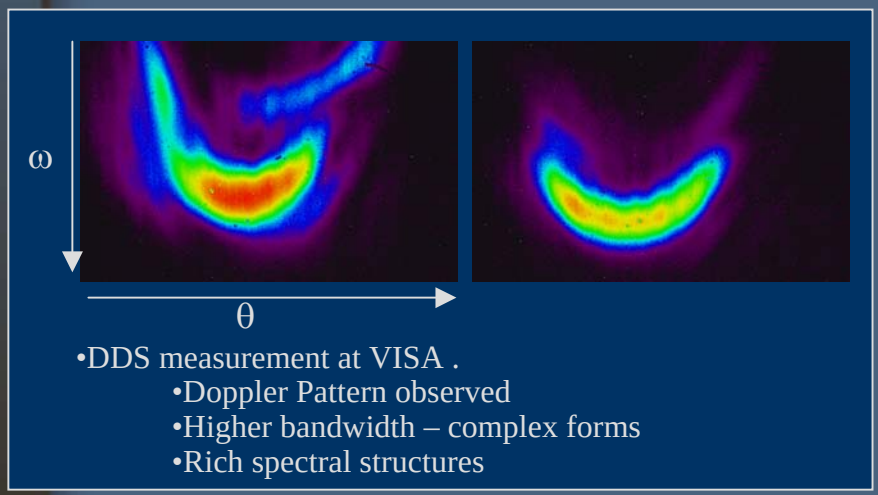
VISA IB: New Diagnostics



Double differential spectrum: Experimental Setup

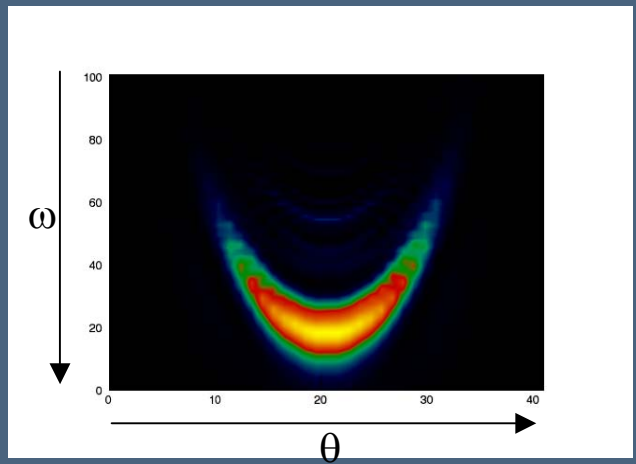
- Double Differential Spectrum (DDS)
  - Unfolds correlation between angle (slits) and frequency (gratings)
  - Preliminary setup
    - improvements coming
    - calibration
    - cylindrical lenses or mirrors
    - graduated slits

$$\frac{d^2 I}{d\omega d\Omega}$$



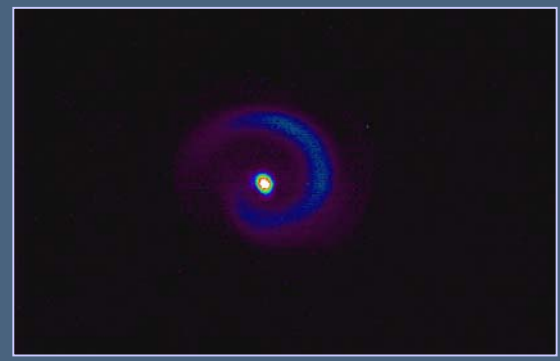
•DDS measurement at VISA .
- •Doppler Pattern observed
- •Higher bandwidth – complex forms
- •Rich spectral structures

Genesis Simulation of DDS for VISA IB running conditions



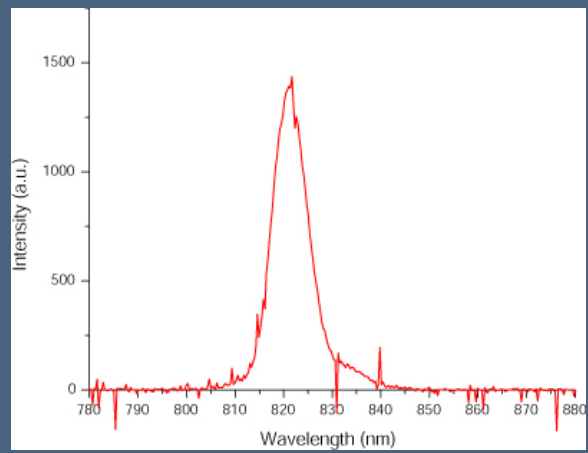
DDS Angular Distributions

Far Field Angular Distribution patterns for FEL in “low” bandwidth regime



with reference laser

- Far field radiation patterns
  - Angular distribution
  - Screen placed approx. 3 m from Undulator exit (~ 10 Z_R)
  - Structures more pronounced than VISA I
  - Need more STE
  - Orbital Angular Momentum of Light?
    - Cylindrical lens setup

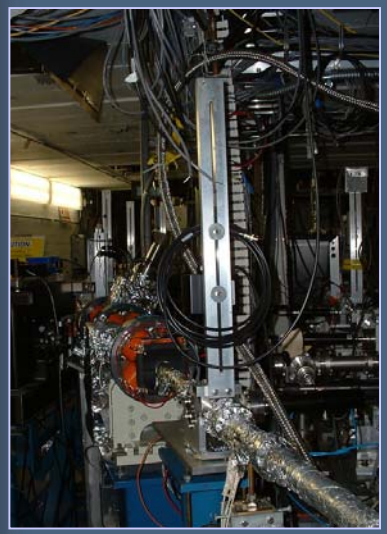


Observed Spectrum at dds measurement

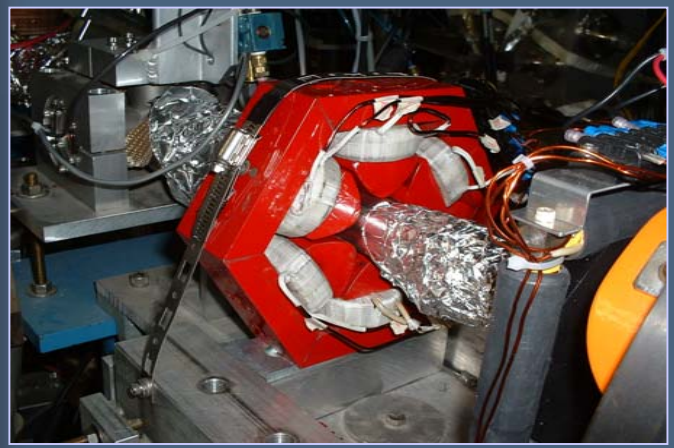
VISA IB: Summary

- SASE FEL is a robust system
  - chirped pulse amplification is possible at ATF
- Parasitic broadening of spectrum should be avoided at VISA II
  - need to steer correctly
  - need to cancel second order dispersion
- DDS and Angular Dist. Profile
  - great additions to our “toolbox”
  - improvements
- STE building up our confidence
- On to VISA II…

VISA II



Modified F-line: BPMs (left) and steering coils (bottom).



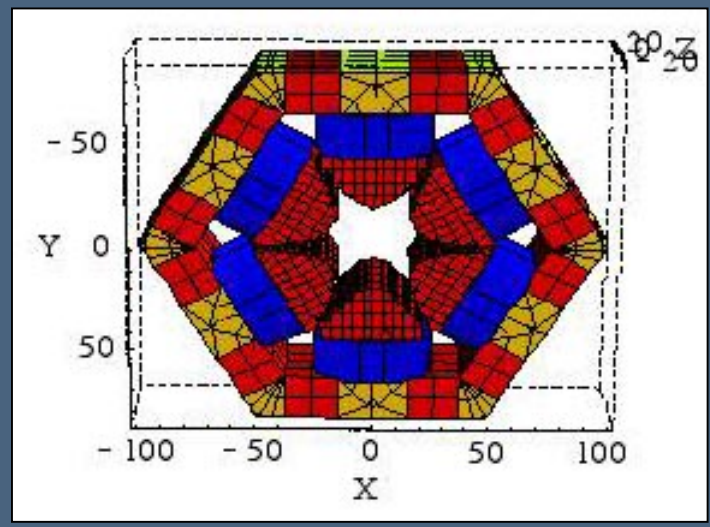
Sextupole in F-line

GOALS

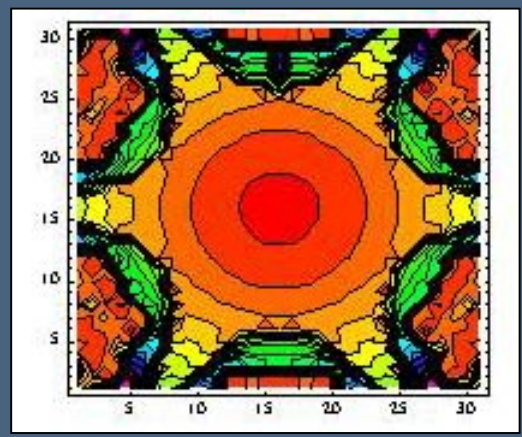
- Linearize F-Line
  - measure T_{166}
- Energy chirp SASE FEL Operation
- Develop new diagnostics
  - DDS
  - Grenouille
  - Compression
- STE Simulation Studies
  - e-beam
  - FEL
  - FROG

VISA II: Sextupoles

- Correct 2nd order dispersion errors locally near quads (areas of high dispersion)
  - longitudinal aberration
    - T_{566} matrix term
- Specs
  - Gradient 22.0 T/m^2
  - Length = 5 cm
- Designed and Fabricated at UCLA



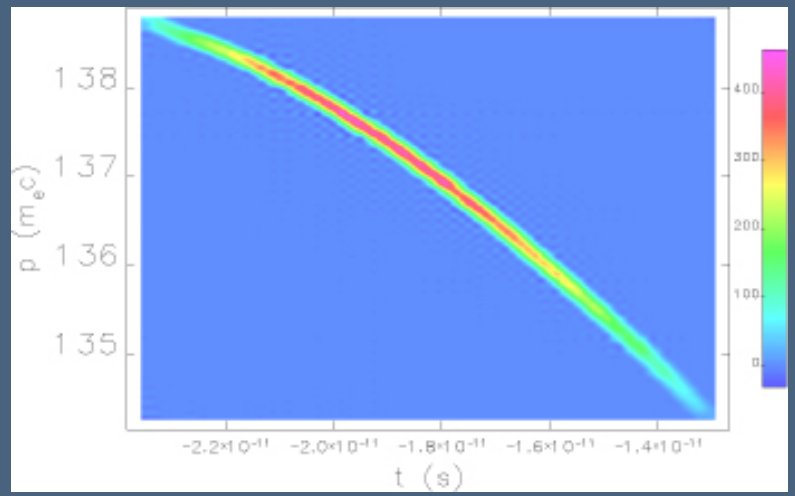
Radia models of sextupole. CAD model (above) field gradient map (below).



R. J. England, "Sextupole Correction…", To be published

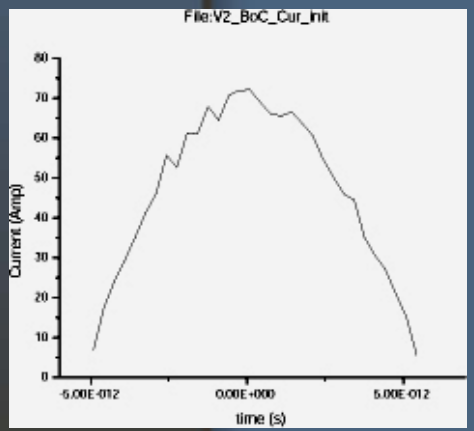
VISA II: Chirped beam (STE)

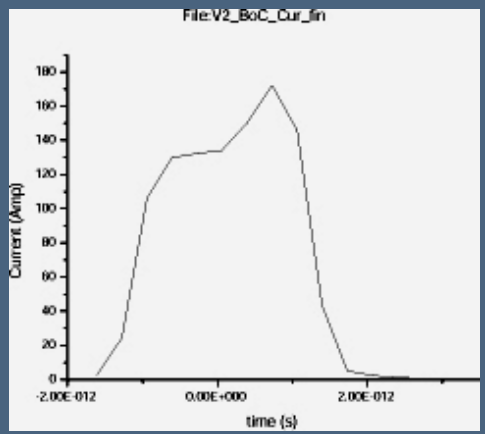
- VISA II: Running conditions
  - Back of Crest Acceleration
  - approx. 2% chirp transmitted
  - negative R_{56} compression
  - ~70% Transmission
    - collimation at HES
  - Linearize F-line (sextupoles on – kill T_{566})

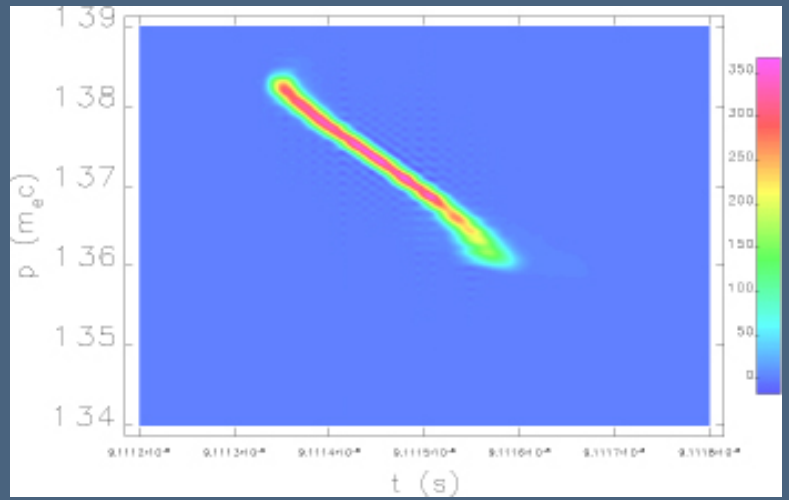


Longitudinal Phase Space for VISA II Case post linac (above) and pre-undulator (below).

Current profile after linac (right) and before injection (left)[Elegant]







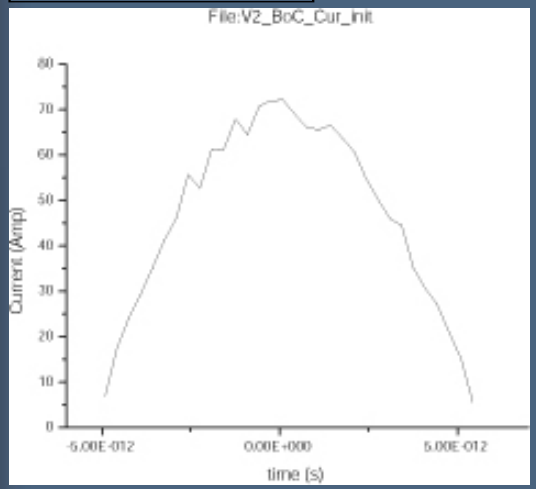
high current, low emittance → high gain FEL, short pulses

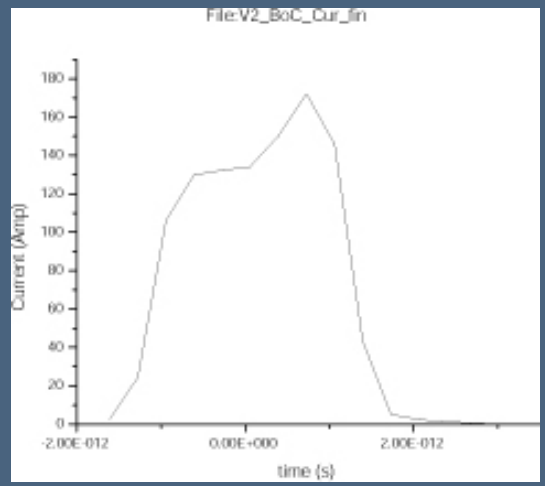
VISA II: STE

Post linac

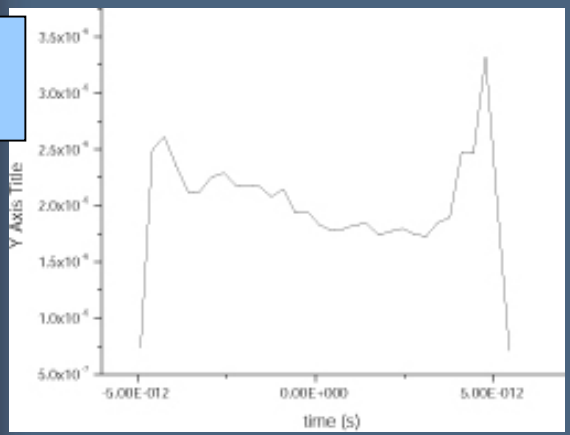
Pre undulator

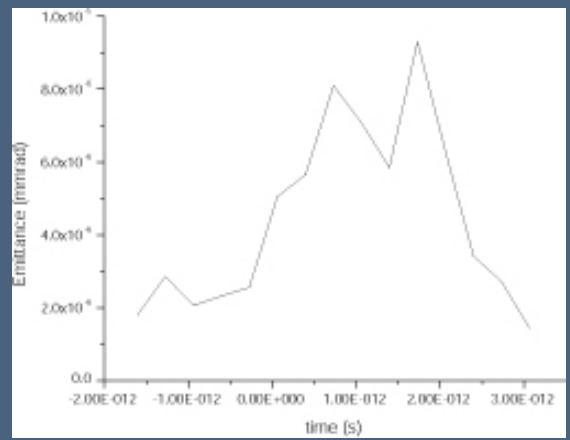
Current





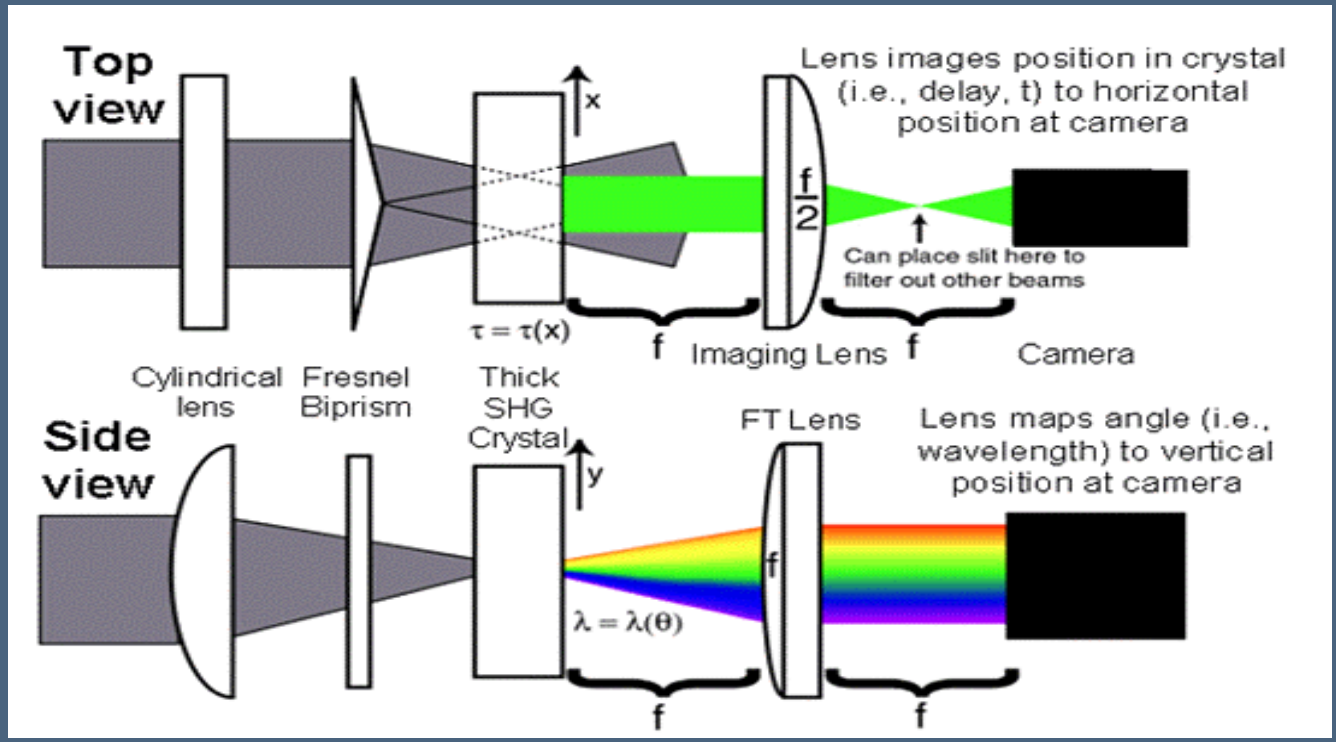
Slice Emittance





- high current (~150 A)
- low emittance
- high gain (~10^6)
  - time-freq. chirp
  - measure?

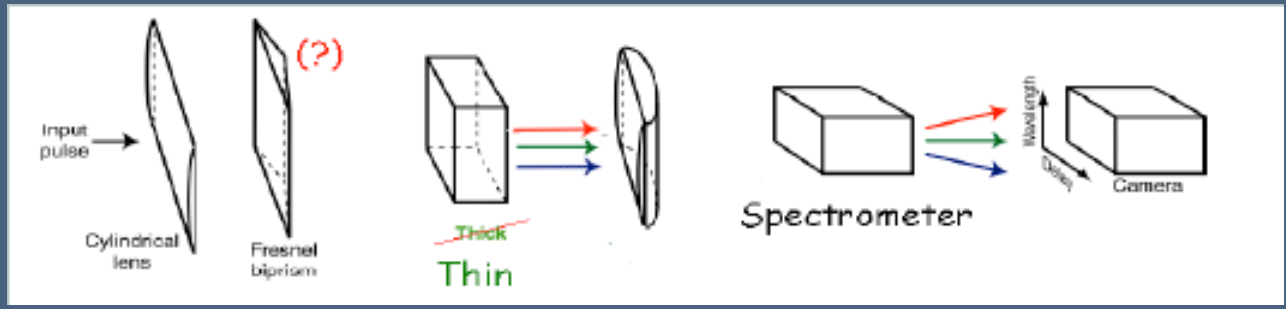
Grenouille



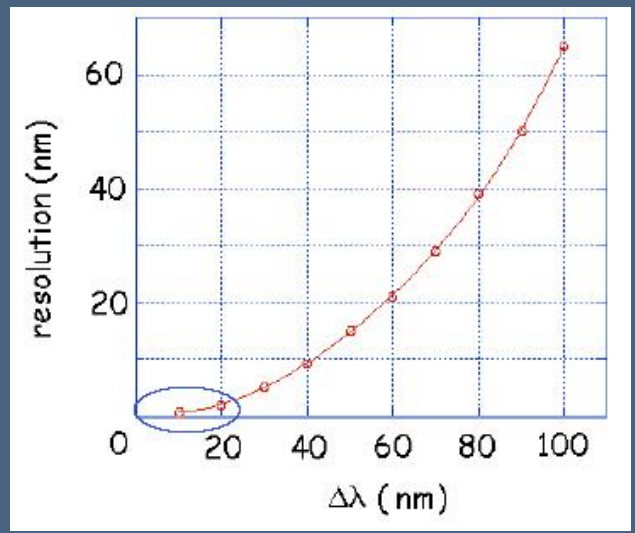
R. Trebino, Swamp Optics, "http://www.swampoptics.com"

- Grenouille
  - Simplified FROG
  - Single shot,
  - auto-aligning, compact
  - yields full pulse phase and intensity identical to SHG FROG

Grenouille Modified

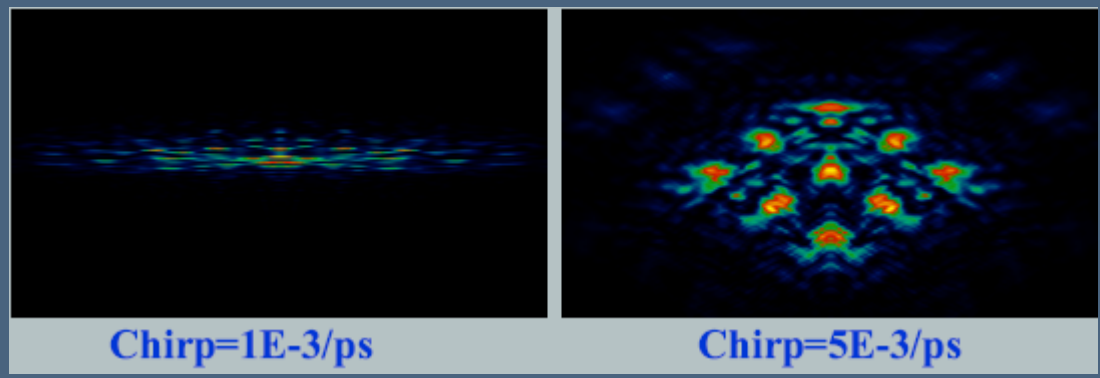


- Grenouille
  - yields full pulse phase and intensity information (SHG FROG)
  - negative and positive chirp have identical traces
- Resolution
  - System is too constrained by doubling crystal
    - Replace thick crystal with thin crystal and spectrometer
- Cutting edge measurement
  - Interrogation on fs scale
  - R. Trebino in advisory role



S.Cialdi, "Temporal Characterization of FEL pulse by Grenouille" , PBPL Seminar Series, Lecture 11

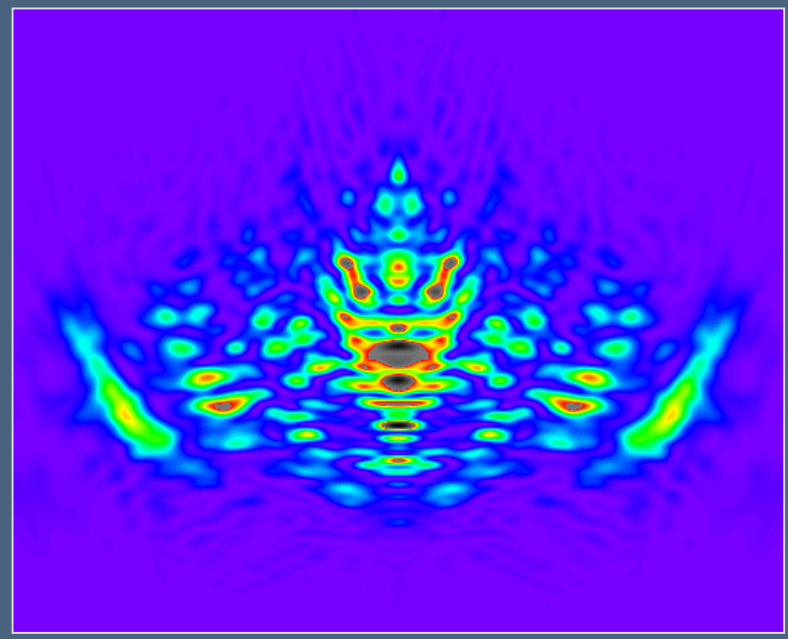
Grenouille Sims (ideal)



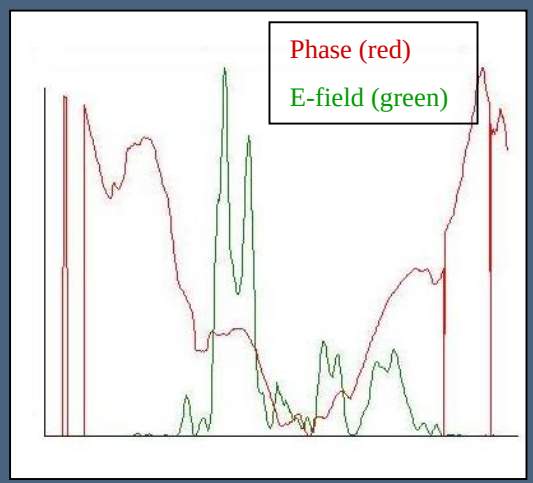
- STE Grenouille output
  - New Genesis Feature
    - ideal beam case
  - Great visualization tool
  - Inversion algorithm robust
  - clear effect for chirped case

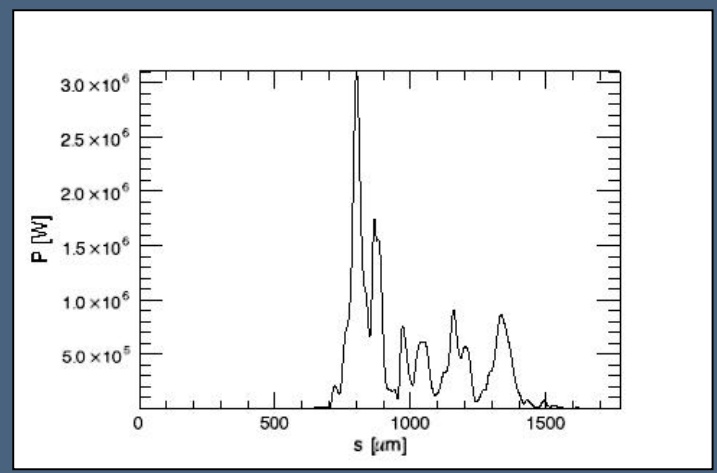
Grenouille Sims: VISA II

- New Genesis feature
- FROG output for VISA II (Genesis)
  - Spectrogram
  - visualize chirp
  - pulse profile is reproduced
  - Power ~ $|E|^2$



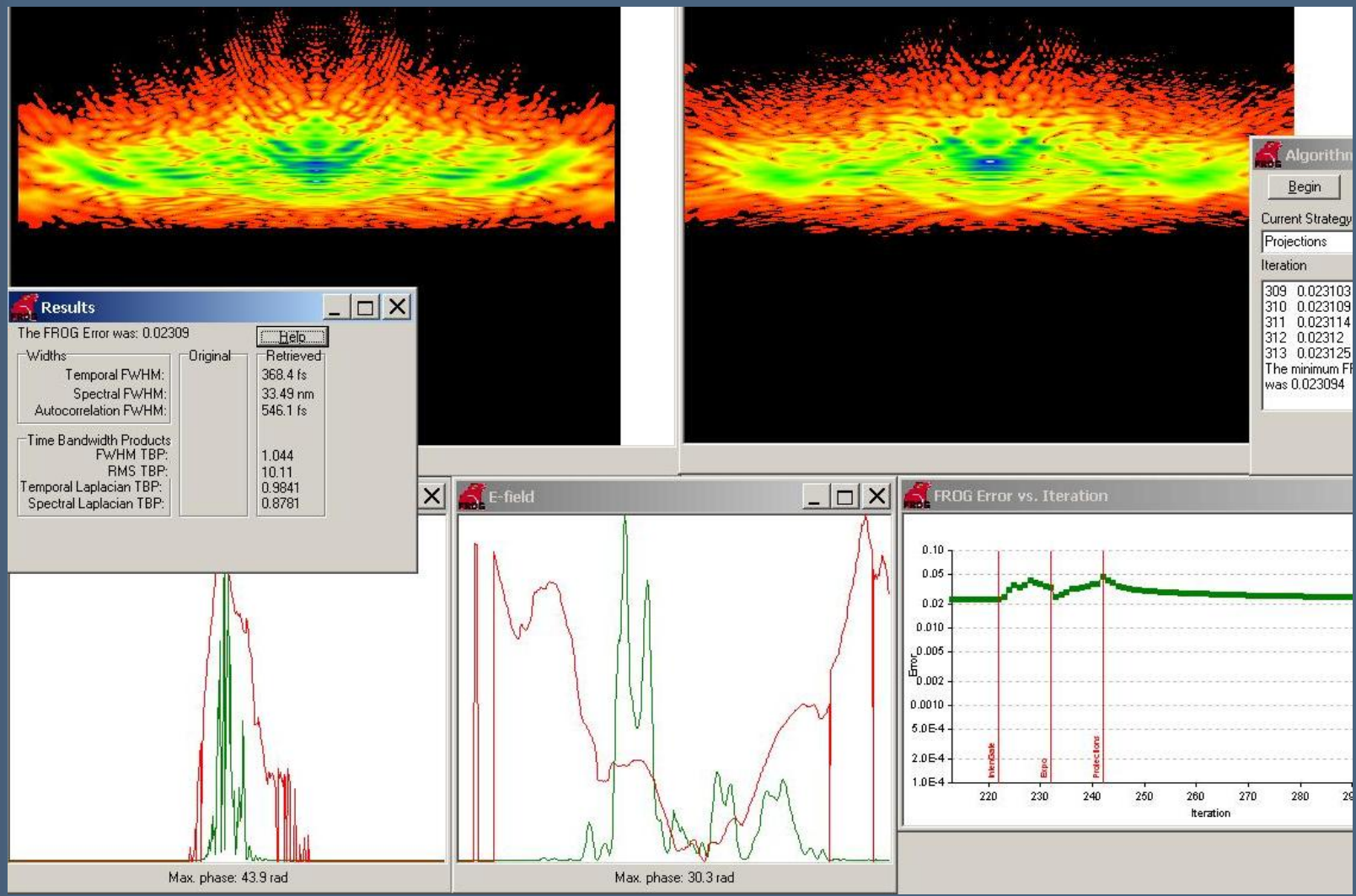
Temporal profile of VISA II pulse reproduced by Femtosoft FROG software (left). Genesis output (bottom right).





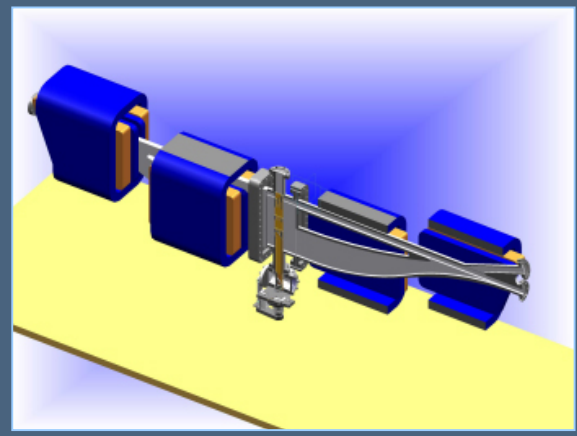
Grenouille Software

FemtoSoft Tech. FROG (unlicensed) Software Screenshot



Chicane

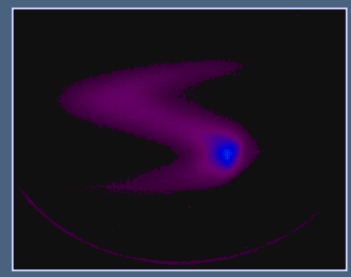
- Specs
  - Nominal Field = 0.2 T
  - Bend Radius = 1.2 m
  - Length = 41 cm
- Compression
  - from 300 μm to 30 μm
- Current
  - up to 1 kA
- Very high gain (STE)
  - saturation in 3rd of 4 m
- Issues
  - implications on future FELS
  - emittance degradation
  - slippage dominated FEL
  - CSR measurement



Chicane Compressor: CAD drawing (top) and installed at ATF (bottom).

Conclusions

- Chirped beam operation
  - with sextupole corrections to second order dispersion
- Hardware Report
  - sextupoles installed
  - chicane installed
- Near Future
  - T_{166},R_{16} measurement (like Neptune)
  - modified Grenouille
  - Orbital Ang. Momentum
- Conclusions
  - complete understanding of beam transport (STE)
  - results pertinent to future FEL operations
  - avoid tick bites 



Beam Profile at FPOP6 with sextupoles on.

Try to avoid January in Brookhaven.