The VISA II SASE FEL Experiment & The ATF Pulse Compressor

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ATF, 1/8/2004

Collaborators

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- ENEA-Frascati: L. Giannessi, M. Quattromini
- INFN-Milano, Univ. di Milano:I. Boscolo, S. Cialdi, A. Flacco
- BNL: I. Ben-zvi, V. Litvinenko, V. Yakimenko

Funding sources

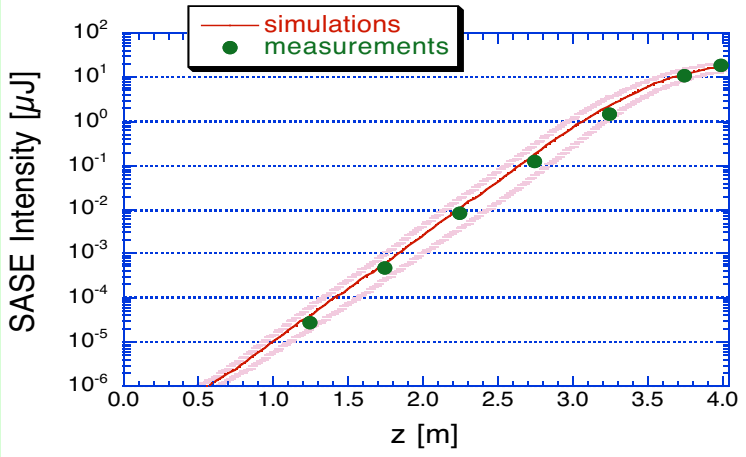
- Office of Naval Research
  - Funded original compressor
  - Major support ending for VISA/compressor this year
- DoE BES (VISA II)
- DoE HEP (compressor)
- INFN (in-kind support for both experiments)
- Proposal in to NSF…

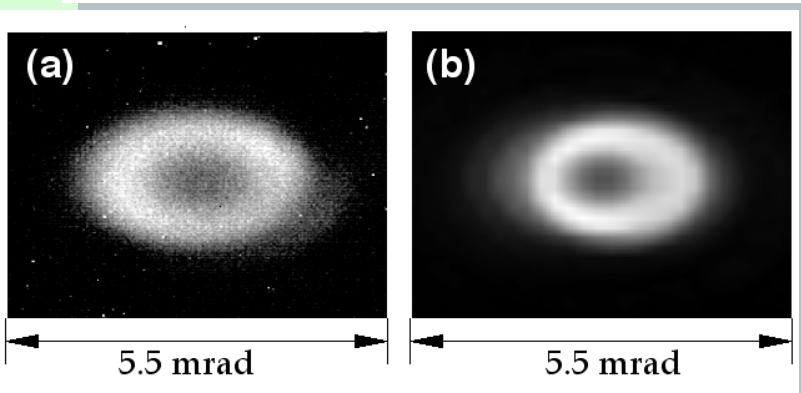
Overview and Goals

- Physics of creating/using high brightness electron beams
  - Advanced accelerators (e.g. wakefield drivers)
  - Radiation production $B = 2I / \varepsilon_n^2$
- Electron beam production is
  - relativistic, one-component, violently accelerating, cold-plasma problem
  - Strongly coupled beam-radiation systems (coherent synchrotron radiation akin to FEL)
- FEL is unique challenge:
  - Merging of electron beam source and radiation physics
  - Merging of computational and experimental physics

Historical background I: VISA

- Major results
  - Anomalous gain due to nonlinear compression in F-line dogleg
  - Shortest gain length ever (<20 cm) in visible-IR
  - Statistics in saturation
  - Higher order angular spectra
  - Developed start-to-end (STE) simulations
  - Higher harmonic gain/CTR
- STE suite of codes:
  - UCLA PARMELA
  - ELEGANT
  - GENESIS
- Rigorously benchmarked to
  - beam measurements post-linac
  - Beam measurements post-dogleg
  - FEL!

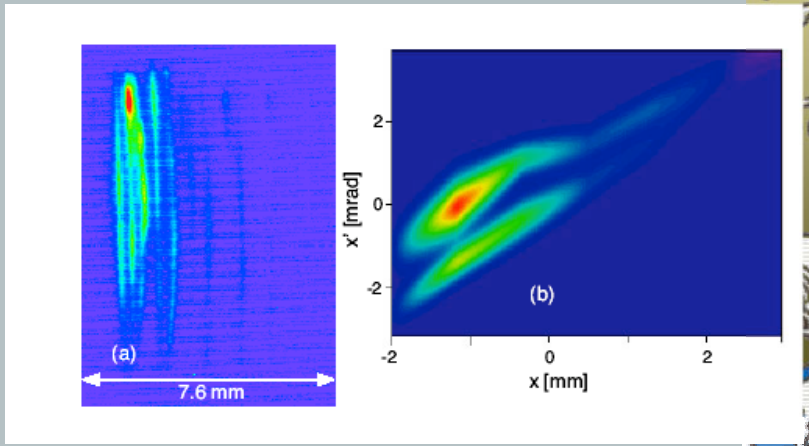




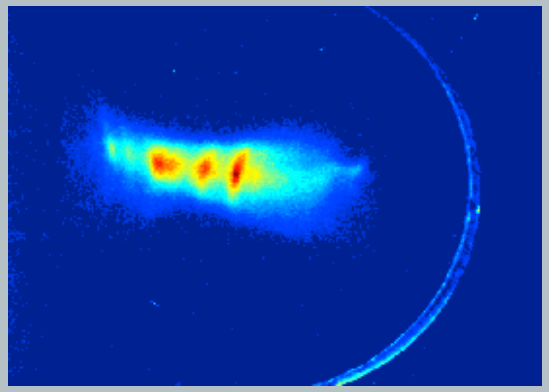
Data (L) and simulation (R) of far-field radiation pattern

Historical Background II: Compressor

- UCLA Neptune experiments at lower energy (12 MeV)
- Noninertial space-charge
  - Dramatic transverse phase space bifurcation
  - Arises from beam velocity fields during folding in *x-z*
- STE simulations
  - UCLA PARMELA
  - TREDI or ELEGANT of accel. fields
- Coherent transition radiation
  - Emittance growth
  - Microbunching instability?
  - Understanding critical to AA/LC and short wavelength FEL in future…



Transverse phase space bifurcation observed at Neptune (S. Anderson)



BNL SDL measurement of microbunching?

Major Publications

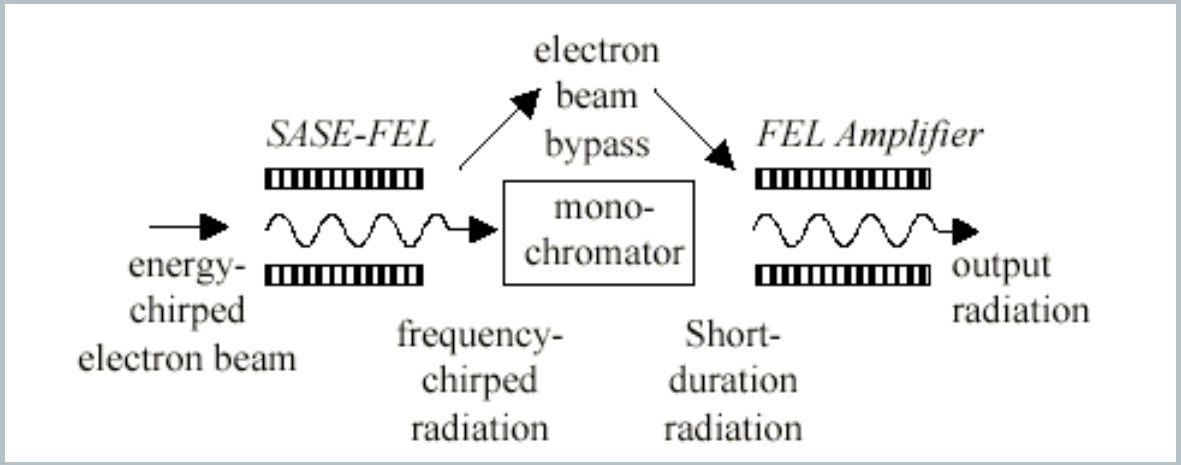
VISA FEL

- 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 the July 2003 issue of the Virtual Journal of Ultrafast Science http://www.vjultrafast.org
- A. Tremaine , et al., “Fundamental and harmonic microbunching in a high gain selfamplified spontaneous emission free electron laser” Phys.Rev.E 66:036503,2002

Compressor

- S. Reiche and J. B. Rosenzweig “Comparison of the coherent radiation-induced microbunching instability in a free-electron laser and a magnetic chicane” Phys. Rev. ST Accel. Beams 6, 040702 (2003). Also published in the July 2003 issue of the Virtual Journal of Ultrafast Science http://www.vjultrafast.org
- S.G. Anderson, J. B. Rosenzweig, P. Musumeci, M. C. Thompson, “Horizontal Phase Space Distortions Arising from Magnetic Pulse Compression of an Intense, Relativistic Electron Beam”, Phys. Rev. Lett. 91, 074803 (2003)

VISA II Goals

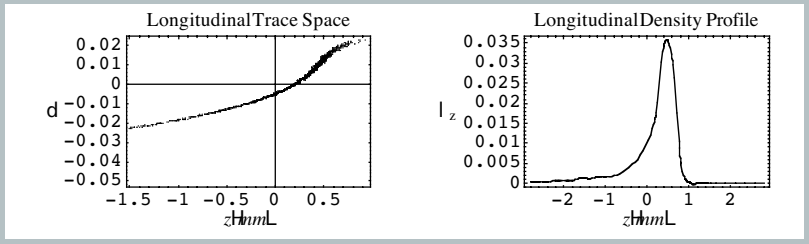


Proposed scheme for creating ultra-short FEL pulses

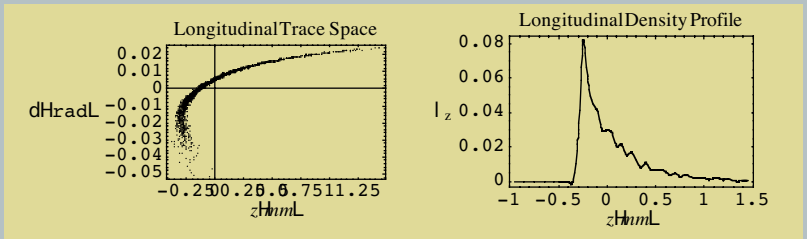
- Explore limits of SASE FEL performance with energy chirp
- Physics underpinning the few fs pulse schemes for X-ray SASE FEL
- Develop advanced beam manipulation and measurements
- New types of FEL diagnostics

Problems with chirped beam transport?

- Dogleg transport is highly nonlinear (T_{566} very large and negative)
- Mechanism for compression in VISA I
- Compensate with sextupoles
  - Expt'ly shown at Neptune
- Linear compression
  - Chirped beam (VISA)
  - Ramped beam (Neptune, ORION)



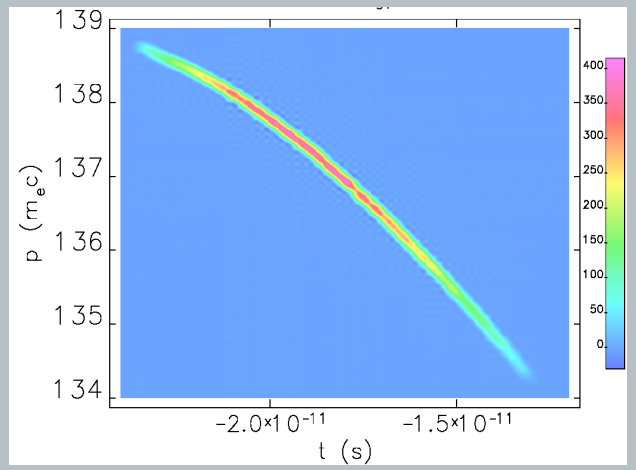
Neptune dogleg without sextupoles (T_{566} = -1.9 m)



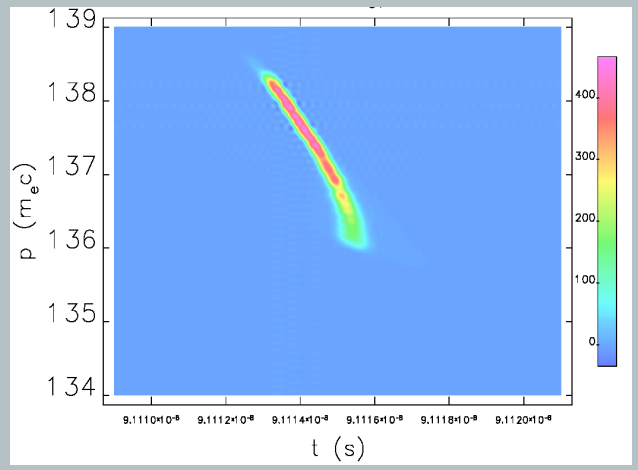
Neptune dogleg WITH sextupoles (T_{566} = 0)

Linear chirping in VISA II

- New linear beamline tune
- Sextupoles provide linearization (kill T_{566})
- Negative R_{56} compression
  - run on-energy
  - back of crest
- Good beam quality obtained
  - 2% energy chirp transmitted

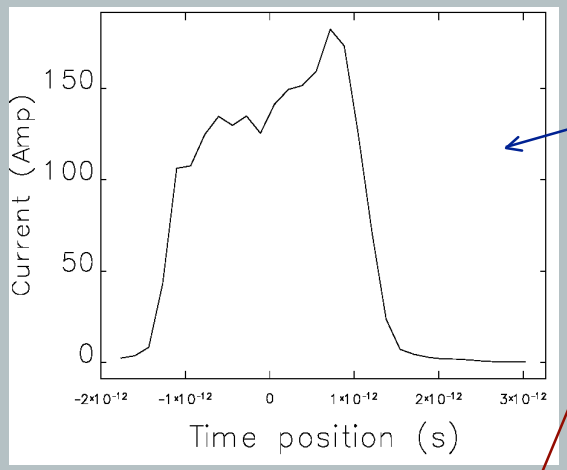


Input longitudinal phase space before dogleg

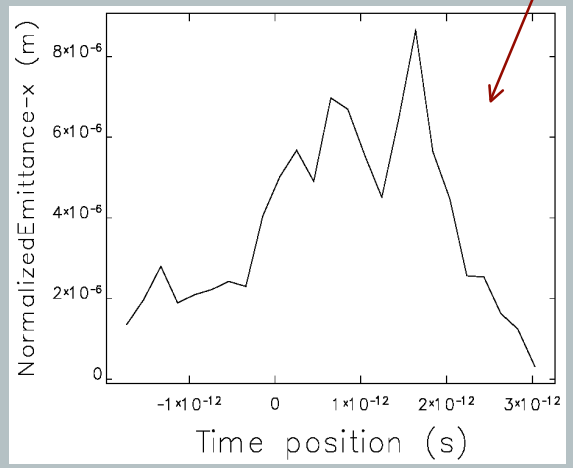


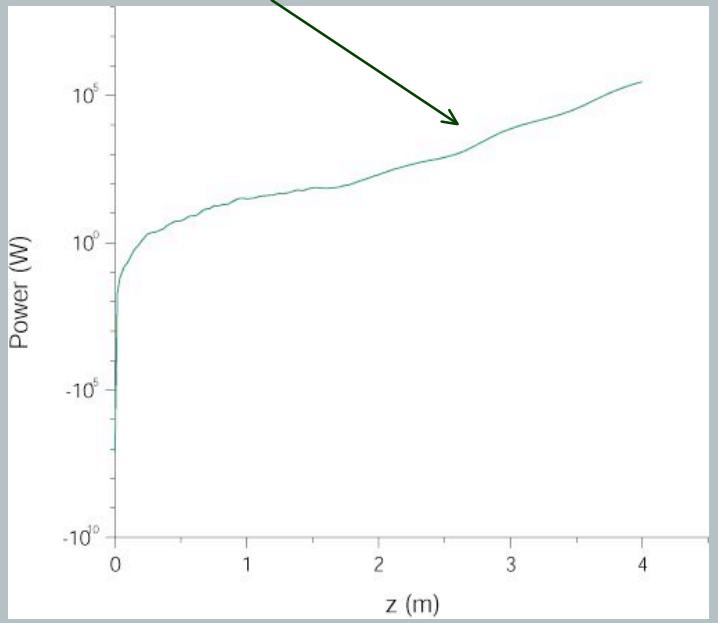
Final phase space including collimation

GENESIS simulation of VISA II

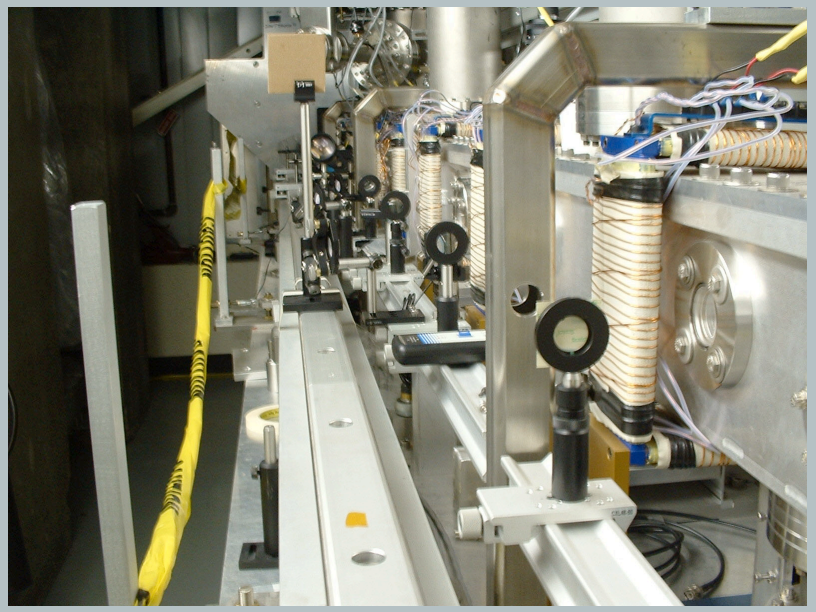


- High current
- Low emittance
- High gain (>1E6) with chirp





A Stepping Stone: VISA Ib

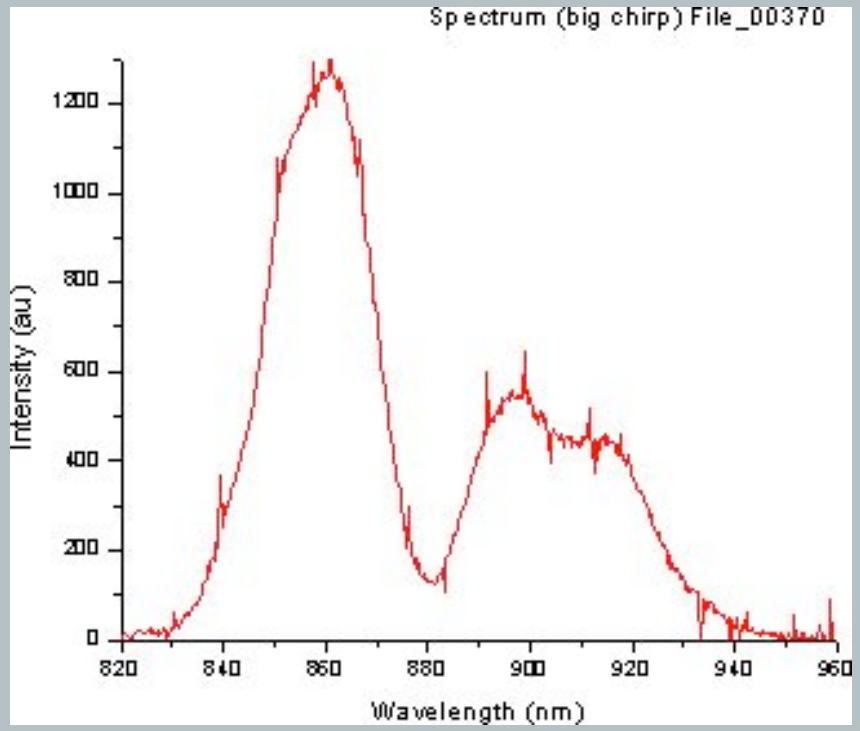


Outside of VISA undulator box with FEL optical diagnostics

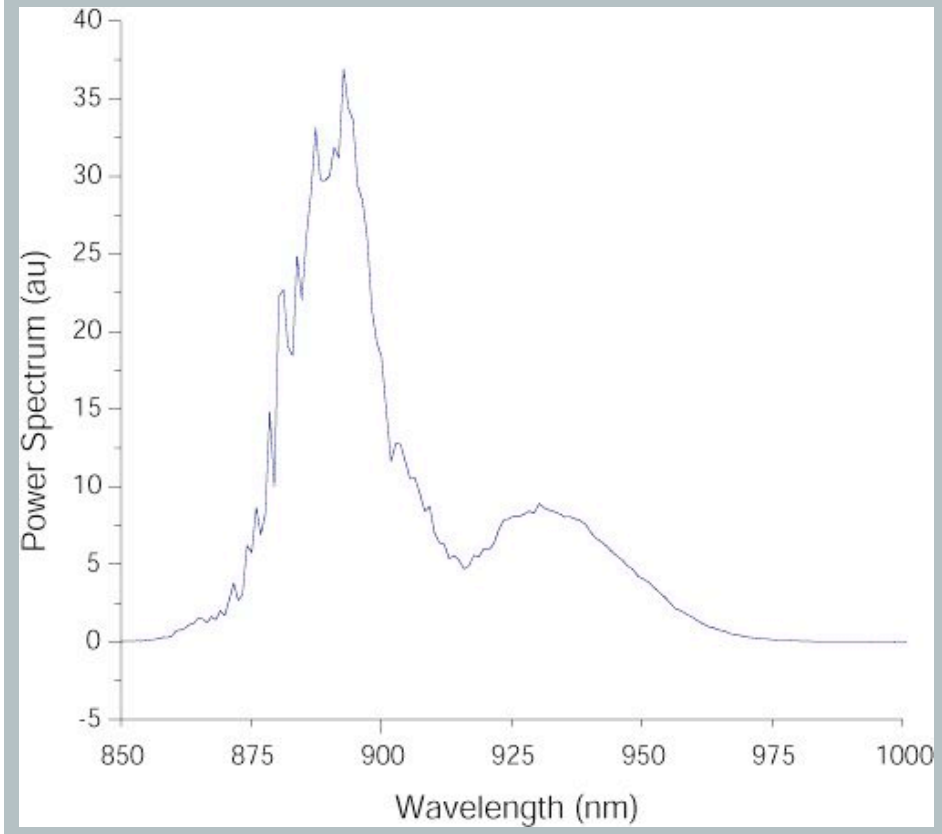
- Recommission FEL while beamline modifications are made
- Run FEL with VISA I-like tunes, but with high chirp
- Develop new FEL diagnostics

Anomalously broad wavelength spectrum observed

- 11% total bandwidth with high gain!
- Only 2% energy bandwidth allowed by slits
- Very reproducible
- Accompanied by wide angular spectrum



STE GENESIS Output Reproduces Spectrum!



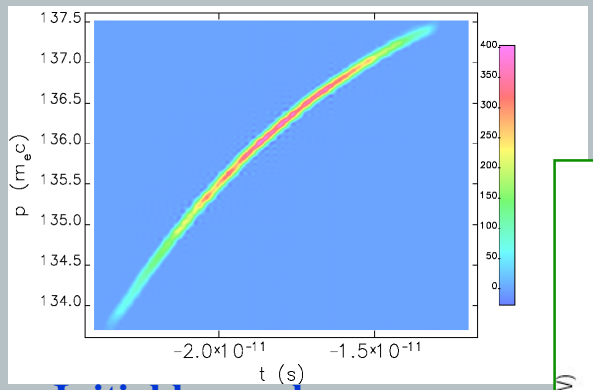
- Running without energy spread in GENESIS gives same result
- Angles important!

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

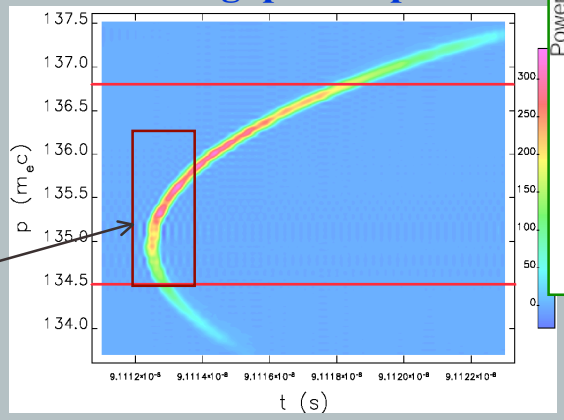
- GENESIS able to handle off-axis Doppler shift by modal breakdown

VISA Ib compression and gain

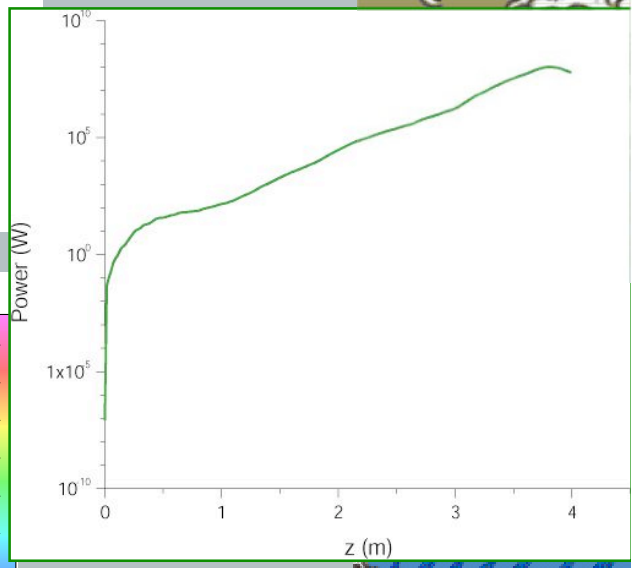
- Portion of beam always in "correct" nonlinear compression region
  - Positive R56 compression, beam forward of crest
  - Stable operation
  - 40% beam collimation
- Very high current
  - >300 A peak
  - <50 fs lasing peak
- Emittance growth high from nonlinear dispersion mismatch



Initial long. phase space



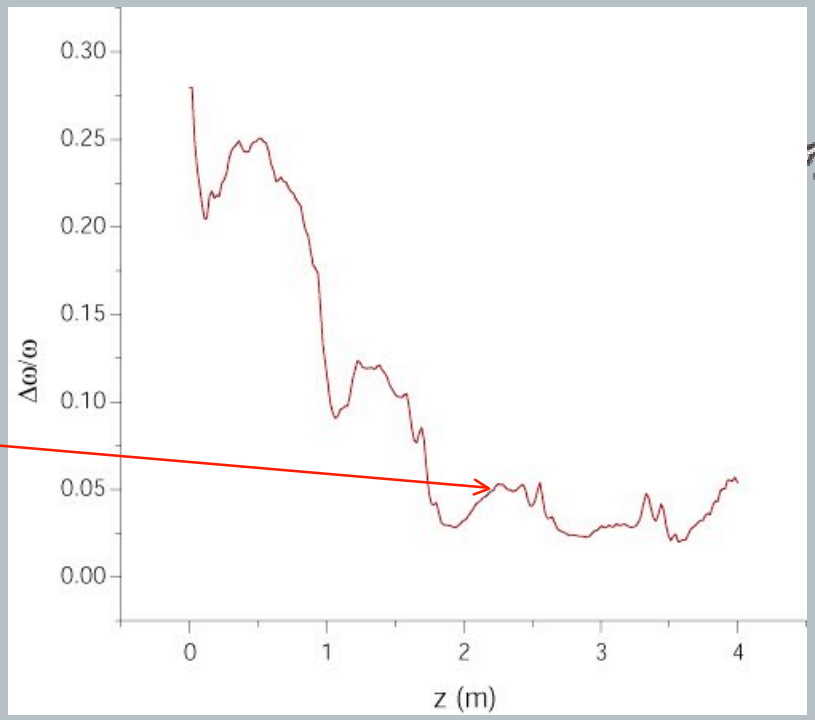
Final long. phase space, showing collimation momenta



FEL just into saturation

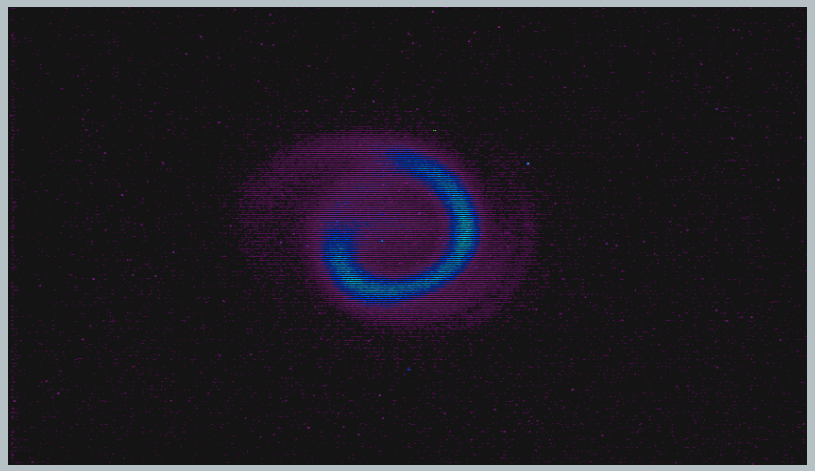
Evolution of bandwidth

- Simulated bandwidth oscillates with same frequency as betatron motion
- Bandwidth maximized near rms beam width maxima; also angular maxima in *strong* focusing…
- Mismatch due to dispersion

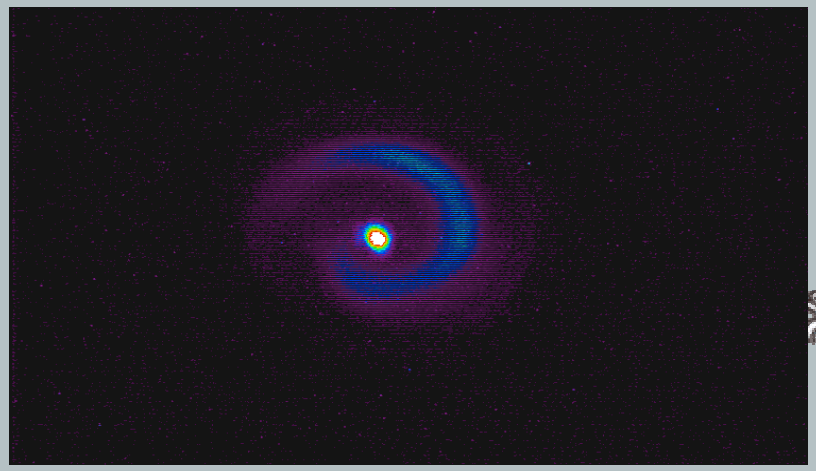


FEL bandwidth as a function of distance along undulator

VISA Ib: Far-field radiation patterns



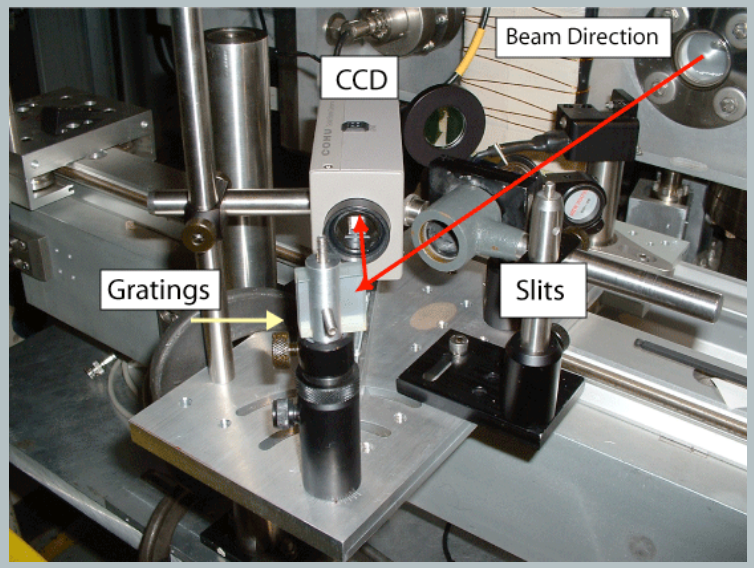
Far field intensity pattern



Far field intensity pattern
With alignment laser

- Detector placed 10 Z_R past undulator exit
- Even more pronounced structures than in VISA I
- Consistent with wider wavelength spectrum

Double differential spectrum diagnostic

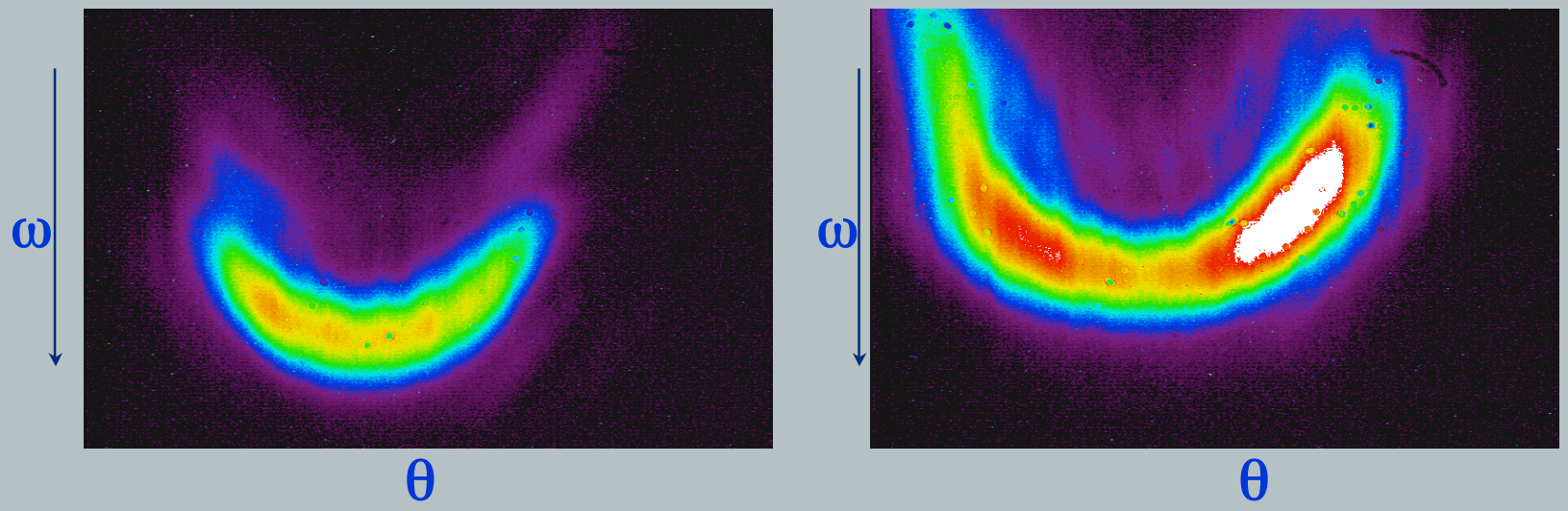


- Radiation theory in general, and FEL in particular, most often cast in double differential form

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

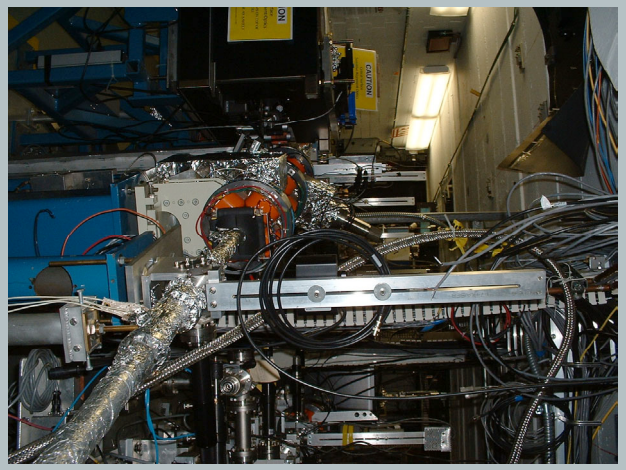
- Unfold the correlations between angle and wavelength

DDS Sample Results

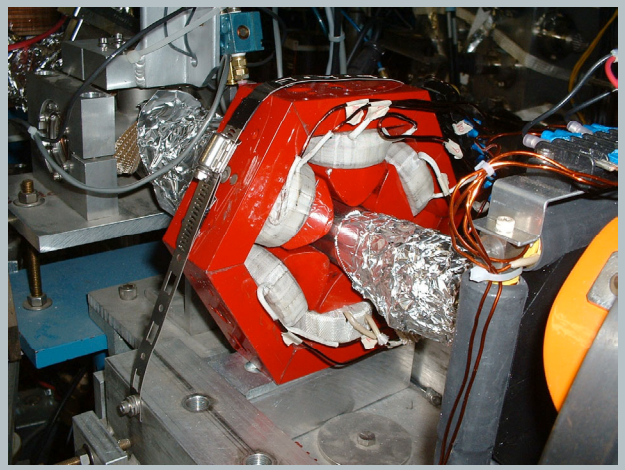


- Normal Doppler pattern observed
- Anomalous pattern observed with higher bandwidth
- Rich spectral structures
- Now being analyzed for publication.
  - VISA Ib shows the SASE FEL is much

On to VISA II



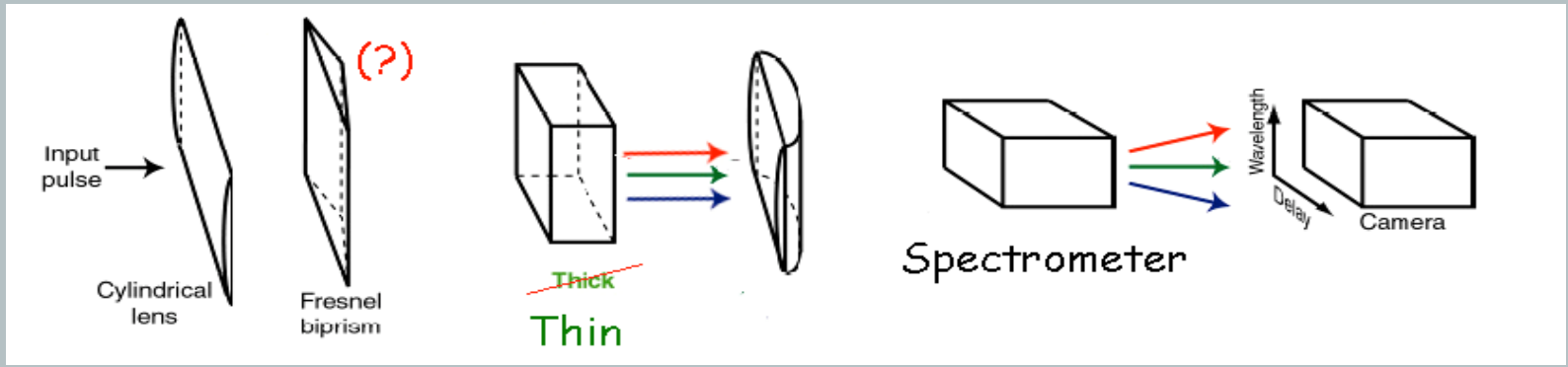
Modified beamline to FEL



UCLA fabricated sextupole at ATF

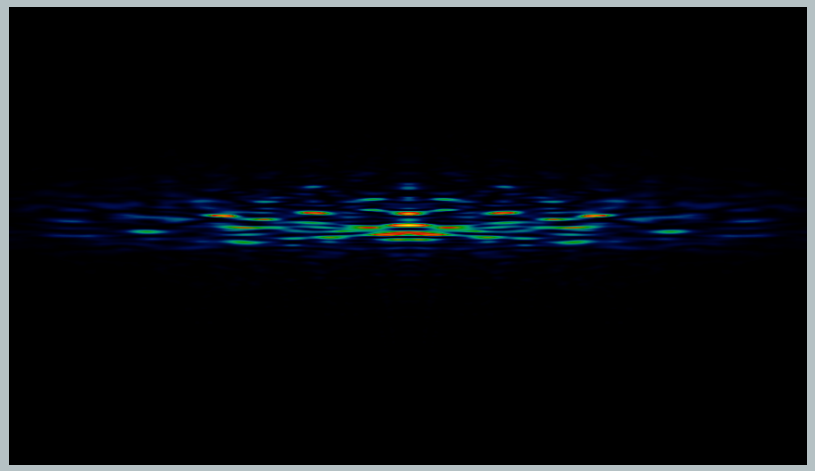
- Beamline (F-line) modifications complete
  - Sextupoles
  - New profile monitors
- FEL diagnostics commissioned
  - Gain v. *z*
  - Spectral
- New temporal diagnostics under development
  - GRENOUILLE
  - Grating compression

Modified GRENOUILLE

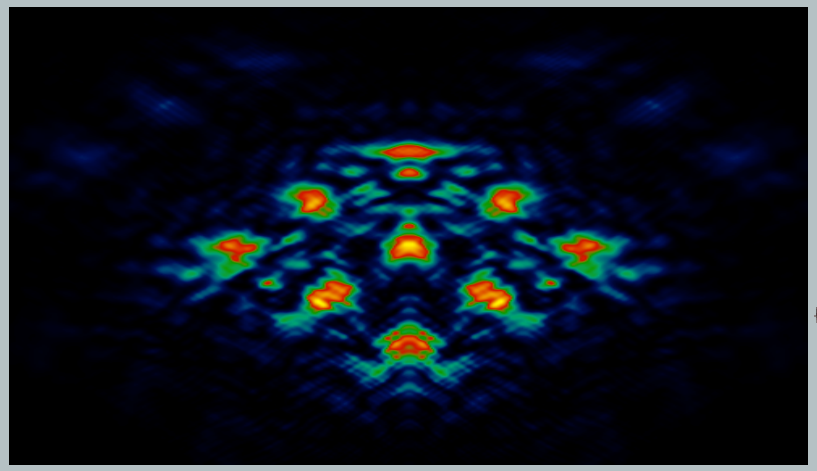


- Study of GRENOUILLE (simplified FROG) indicates that chirped SASE FEL pulse is not easy to measure
- System too constrained by GVD in doubling crystal
- Present solution: replace thick doubling crystal with standard spectrometer

Simulated GRENOUILLE Output



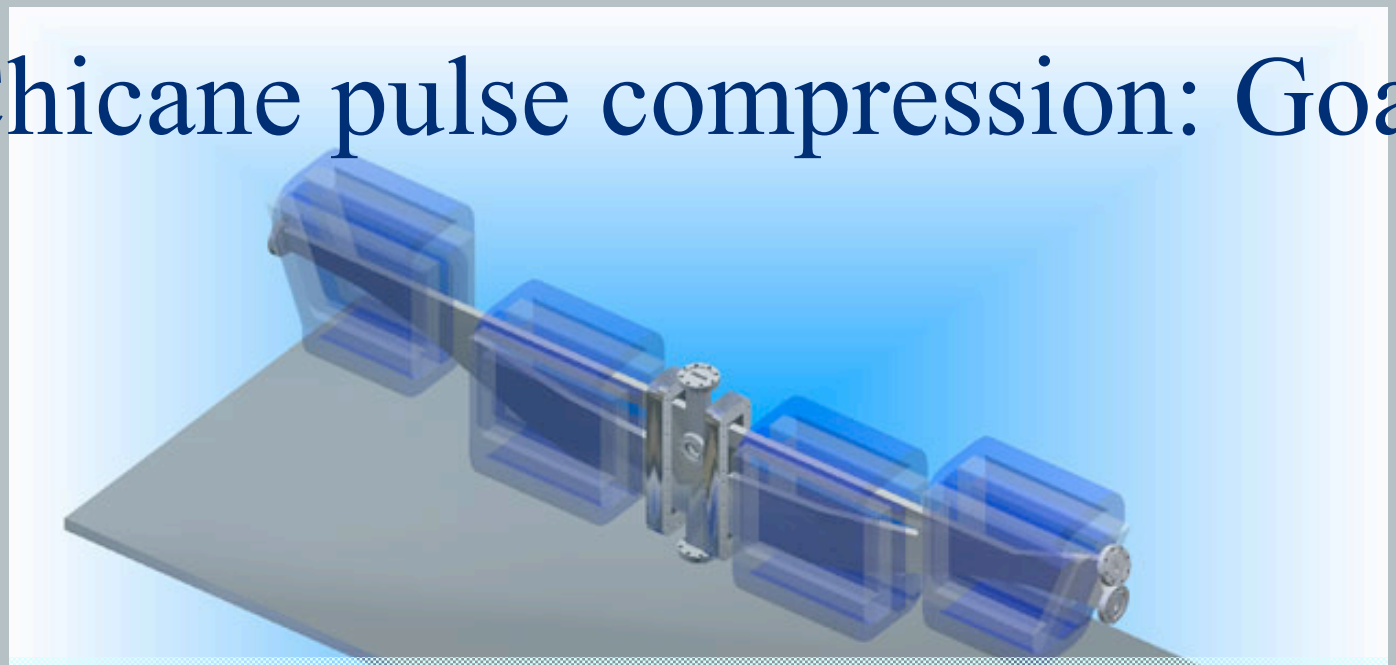
Chirp=1E-3/ps



Chirp=5E-3/ps

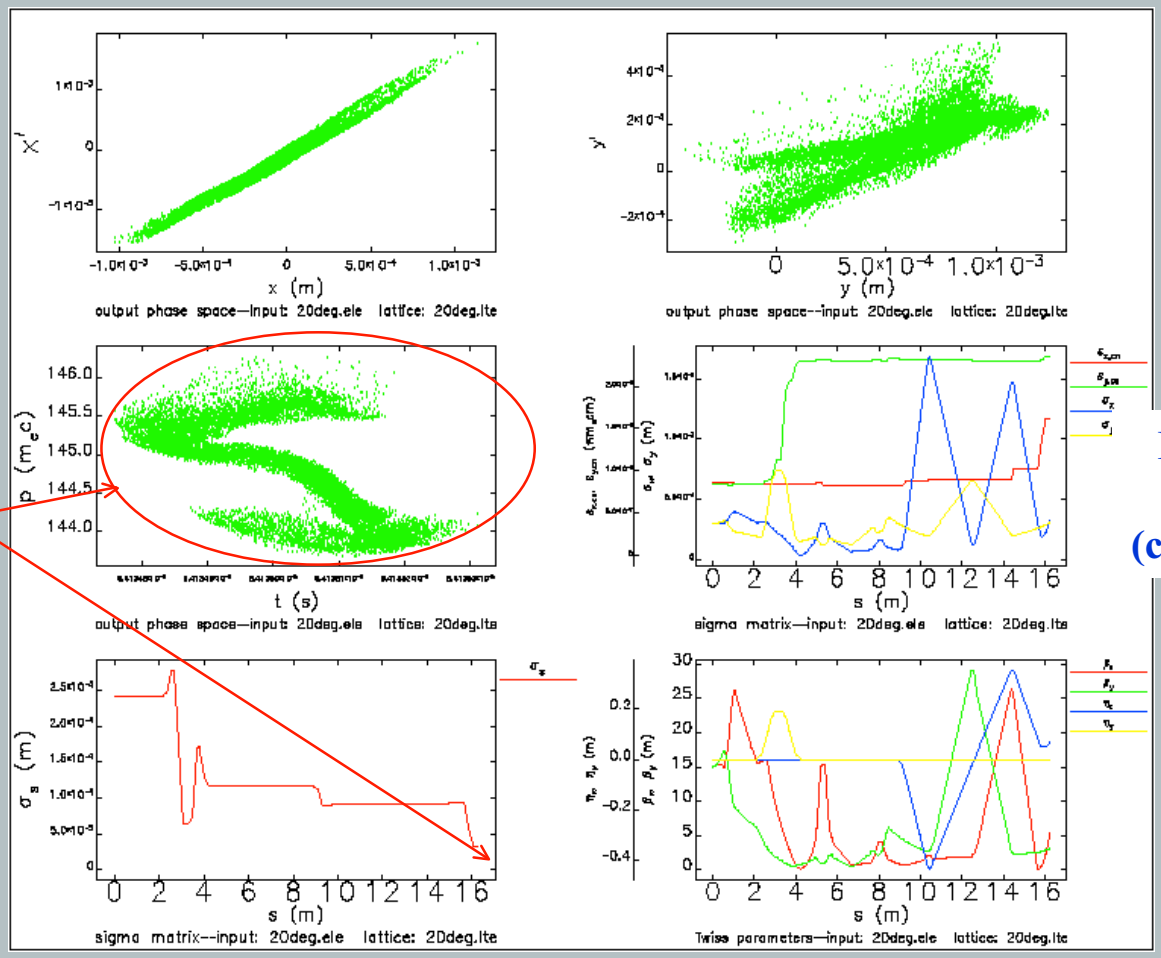
- GRENOUILLE output simulated with STE
- GENESIS post-processor
- Clear signature from chirped case
- Inversion algorithm robust

Chicane pulse compression: Goals



- Study physics of pulse compression
  - Coherent radiative processes
  - Phase space distortions
- Add capabilities for further experiments at ATF
  - SASE FEL
  - Wakefields (e.g. PWFA at FNAL A0, SLAC FFTB)
  - Use complicated by dogleg transport!

Use of BL1 with compressor



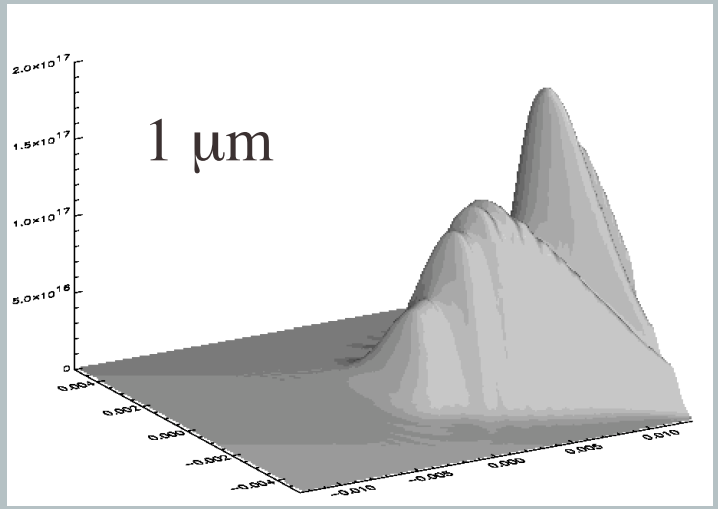
65 fs rms bunch length

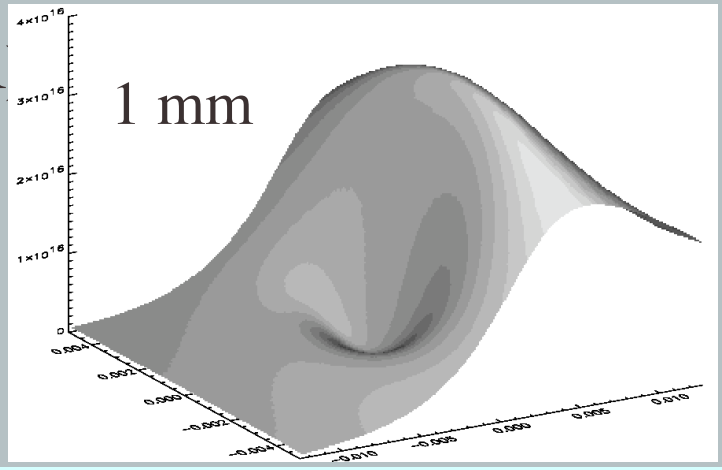
Emittance growth in both planes (chicane v, dogleg h.)

R56 is up to 3.5 times larger (+) in the chicane than in the dogleg (-)

Collective physics issues in compression

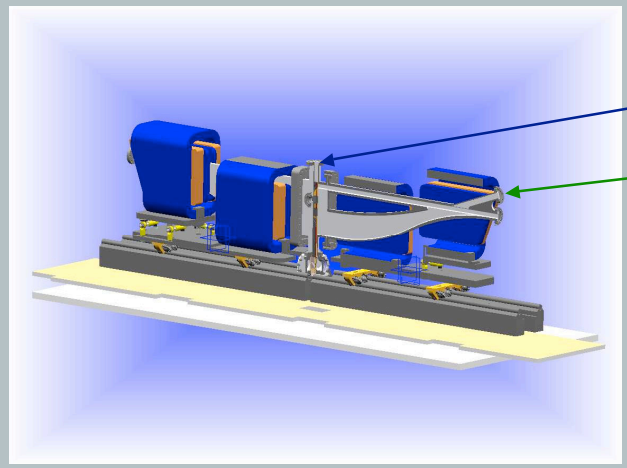
- Coherent synchrotron radiation (CSR) observed at many labs
  - Is CSR responsible for beam microbunching?
- New physics?
  - Coherent edge radiation (CER) is major focus of our initial experiments
  - Examine acceleration v. velocity field effects
  - Phase space distortions: *z, x*





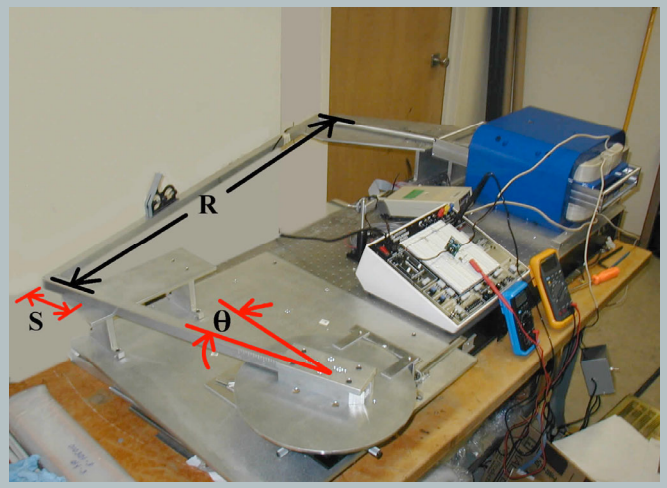
Coherent edge radiation (numerical simulation of UCLA/BNL/INFN expt.)

UCLA/ATF chicane



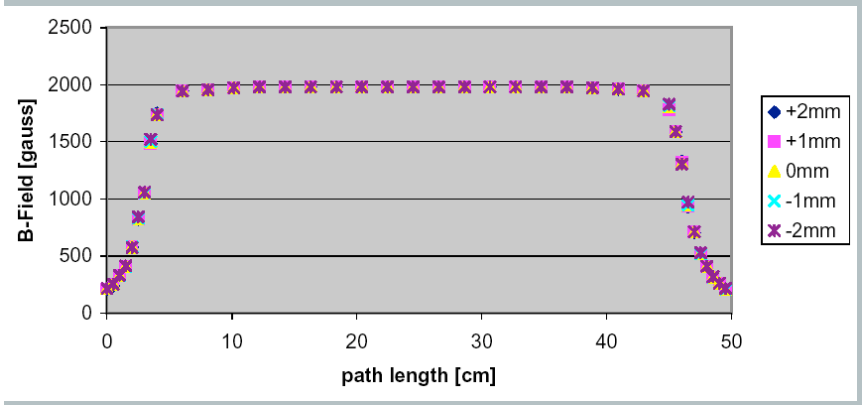
- Chicane fabricated and measured at UCLA
- Installation completed July-Sept. '03
- Custom vacuum chamber
  - Beam diagnostic center
  - CER exit port, points back to final edge of dipole 3, entrance of dipole 4, which radiate constructively.

Magnet testing at UCLA

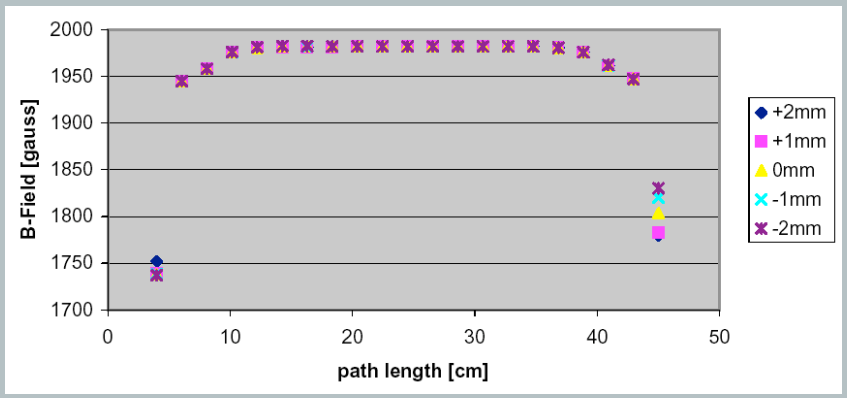


Hall probe constant radius sweeper

- Field flatness checked for all dipoles
- Field uniformity exceeded specification for dispersion mismatch induced
- Excellent agreement with 3D field model (AMPERES)



Full scale (end magnet)



Partial scale

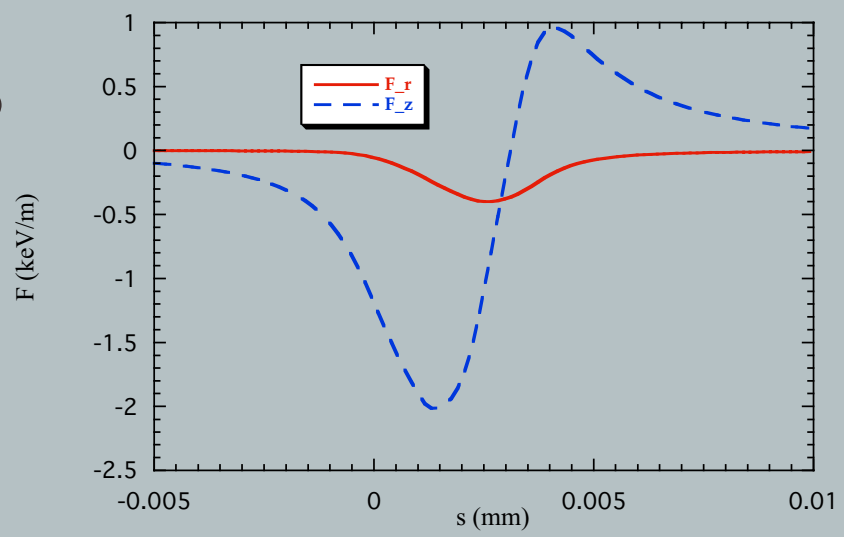
CER Diagnostic system

InfraRed Labs bolometer

- Radiation transport outside of injector bunker
- Liquid He-cooled Si bolometer
- Resolve CER with high pass filters
- Cold filter wheel with cut-on wavelengths:
  - 13, 27, 45, 103, 285, μm none
- System nearly complete
- Angular information?

Advanced modelling of CER/CSR

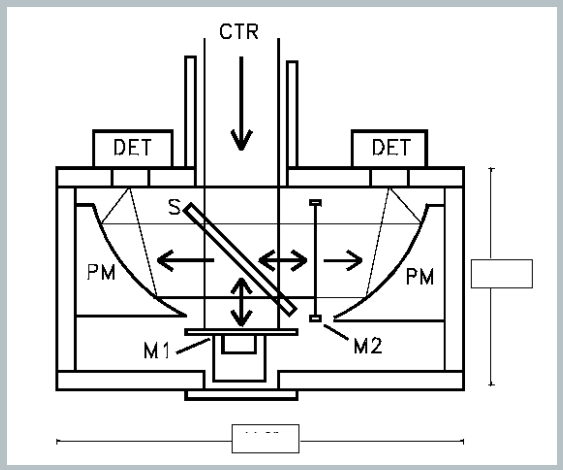
- ELEGANT 1D model not to be trusted in short pulse regime, even for energy loss
- We need *field information* to predict CER/CSR spectrum in experiment
- Extend TREDI
  - 3D Lienard-Wiechert
  - Working with Giannessi and Quattromini
  - Results in coming weeks



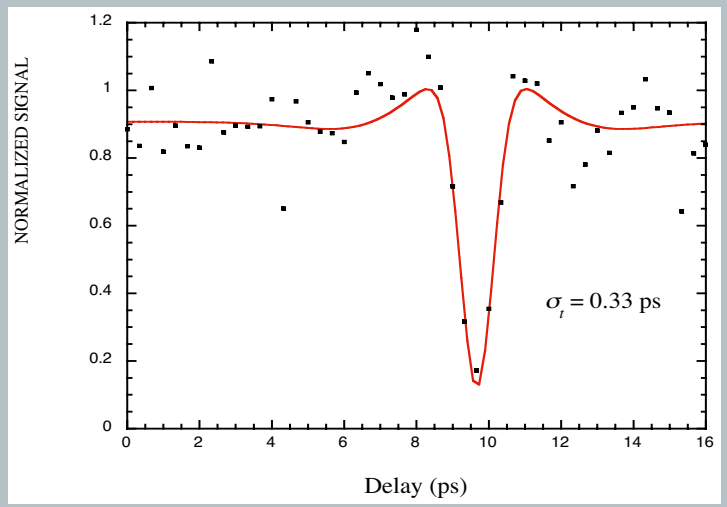
Sample CSR "wake" calculation using TREDI

Other ultra-fast beam diagnostics: Coherent radiation

- Coherent transition radiation (CTR) interferometer downstream of chicane for independent determination of bunch length
  - New model from U. Happek
- Momentum spectrum at first dogleg dipole
- Transverse phase space tomography for phase space distortions



Hi-res Michelson for CTR



Recent measurement of velocity bunching at LLNL PLEIADES

Crystal ball

- VISA II fully-funded only through this year
- In the coming year at VISA II
  - Chirped beam operation
  - Advanced diagnostics
  - Thesis of G. Andonian
  - NSF can continue… lots of ideas for high gain studies
- Compressor
  - Power up within weeks, transverse studies start
  - Coherent radiation diagnostics ready in late winter
  - Thesis of C. Vicario
- Applications of compressor next