Beyond SASE and Saturation

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Presented at SwissFEL & GFA Accelerator Seminars
December 6, 2010

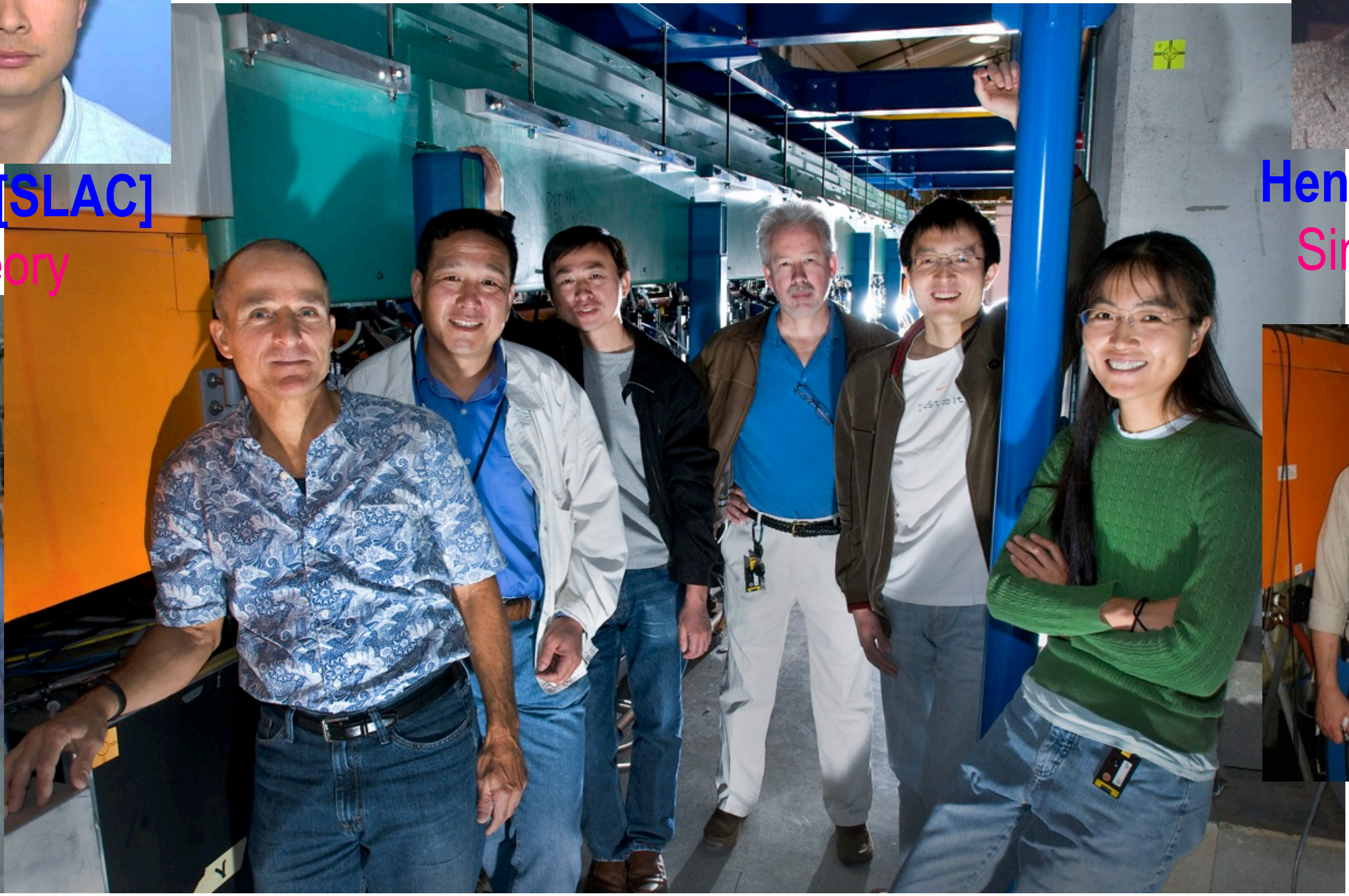
Acknowledgments

Colleague, collaborators and friends from BNL and around the world, specially students and postdocs whom I have the pleasure to work with.

SDL Team

Juhao [SLAC]
Theory

Henry [SAIC]
Simulation



Larry
THz

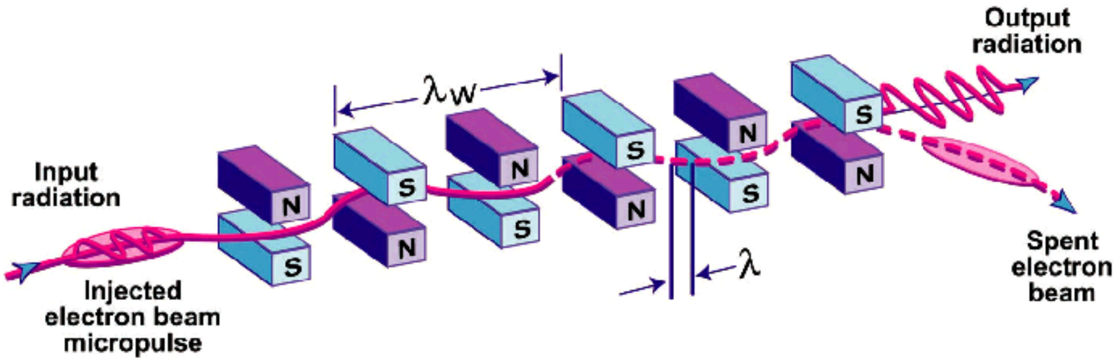
Aditya
RF

Dave	Xijie	Yuzhen	Jim	Houjun	Xi
Engineer	FEL	Laser	Theory	Beam	Beam

Outline

- Introduction
  - NSLS and SASE
  - Self Amplified Spontaneous Emission (SASE) – an efficient noise amplifier.
  - Source Development Laboratory (SDL)
- Beyond the SASE – fully coherent, compact and cheaper
  - ✓ Single-spike (coherent) SASE)
  - ✓ Seeded FEL amplifiers.
- Beyond saturation – tapered undulator:
  - ✓ Efficiency improvement.
  - ✓ Spectra enhancement.
  - ✓ Transverse mode preservation.
- Conclusion remark.

Free Electron Laser Configurations



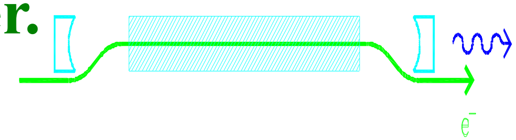
$$\lambda = \frac{\lambda_W}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

•Tunability.

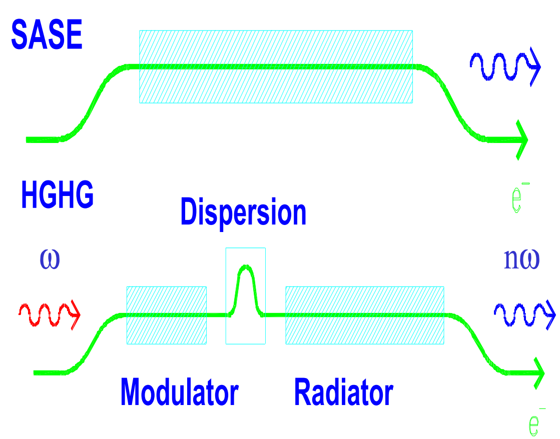
•High power.

- **Oscillator**
  - Fully coherent.
  - Modest beam quality.
  - Limited by the optics.
- **Single-pass amplifier**
  - **Seeded FEL amplifier.**
    - Direct amplification.
    - Harmonic generation.
  - **SASE**

OSCILLATOR



SINGLE PASS FEL



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OPTICS COMMUNICATIONS

Volume 50, No. 6, 15 July 1984

COLLECTIVE INSTABILITIES AND HIGH-GA

R. BONIFACIO *, C. PELLEGRINI

National Synchrotron Light Source, Brookhaven Natio

and

L.M. NARDUCCI

Physics Department, Drexel University, Philadelphia, P

pp. 373–378

http://einstein.drexel.edu/events/narducci/biography/data/fullsize/Rodolfo_Lorenzo_Lucia.jpg

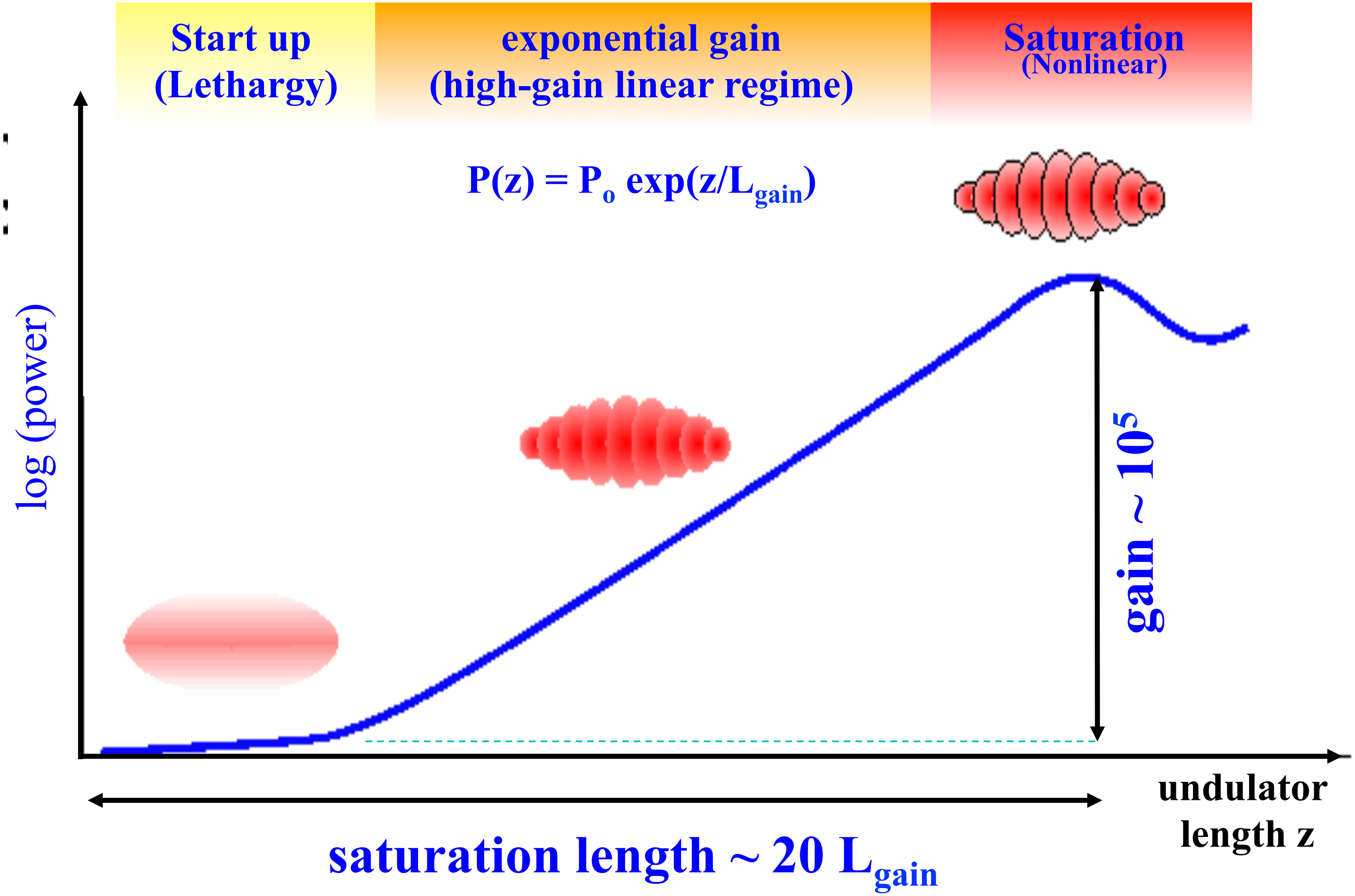
Major FEL Concepts and Mile-Stone Experiments @ NSLS

- Harmonic (Murphy & Pellegrin, 1985).
- Start up (J. Wang & L.H.Yu, 1986).
- Universal Scaling (L.H. Yu et al, 1988).
- HGHG (L.H. Yu,1991).

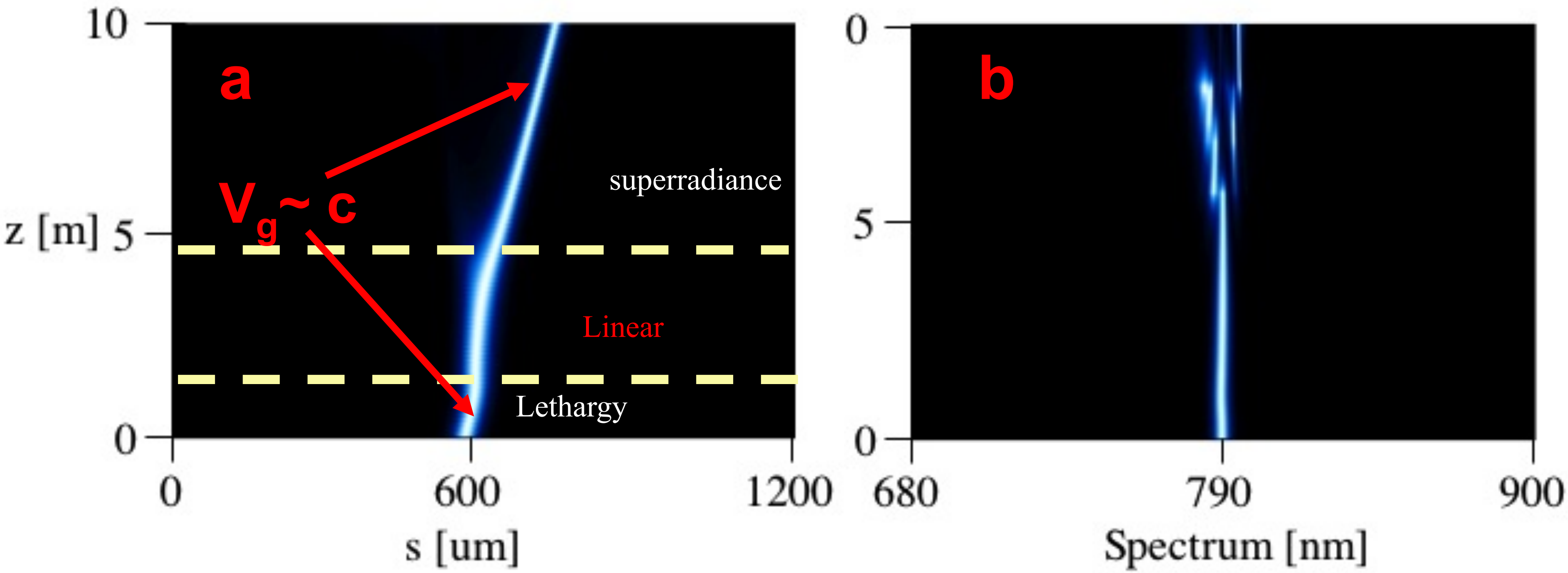
FEL Experiments:

- TOK @ UV-ring (1980s).
- HGHG: 2nd (1999), 3rd (2002) and 4th (2006).
- VISA (2001).
- Superradiance FEL (2006)
- Tunability and FEL control (2006-2010).

Self Amplified Spontaneous Emission SASE



Evolution of FEL Pulses



- Due to noise start-up, SASE is a chaotic light temporally with M_L coherent modes (M_L spikes in intensity profile)

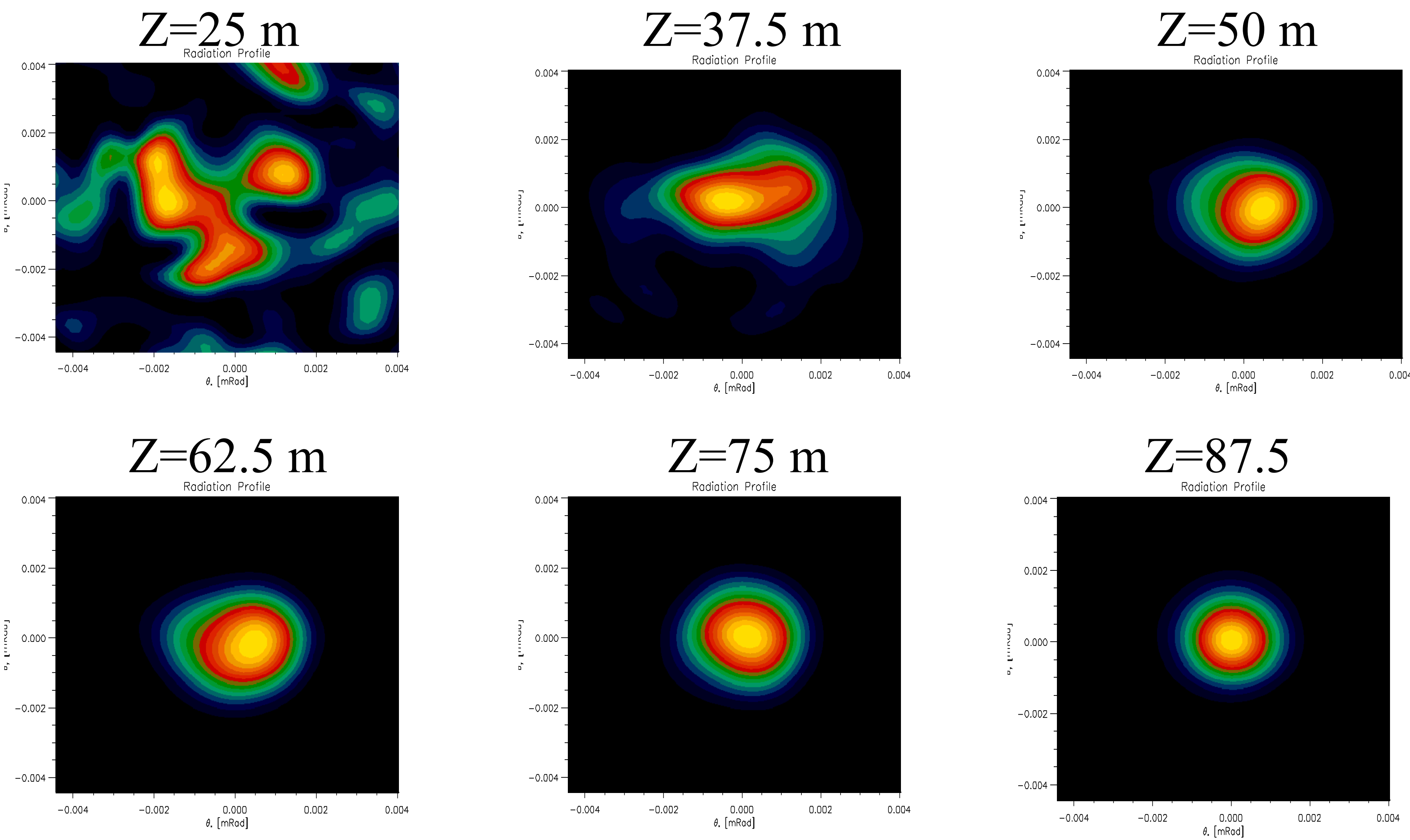
$$M_L \approx \frac{\text{bunch length}}{\text{coherence length}}$$

- Its longitudinal phase space is M_L larger than FT limit (rooms for improve!)

- Integrated intensity fluctuation: $\frac{\Delta I}{I} = \frac{1}{\sqrt{M_L}}$

Z. Huang, NSLS Seeded XFEL Workshop (2002).

Transverse Coherence



Courtesy of S. Reiche (UCLA/PSI)

Realization of Saturated SASE

- APS LEUTL 2001
- NSLS VISA
- NSLS SDL
- DESY FLASH
- SCSS @ Spring-8
- Other places – SPARC, SDUVFEL?
- SNAL LCLS 2009

Saturation of SASE FELs

RESEARCH ARTICLES

Exponential Gain and Saturation of a Self-Amplified Spontaneous Emission Free-Electron Laser

S. V. Milton,[1*] E. Gluskin,[1] N. D. Arnold,[1] C. Benson,[1] W. Berg,[1] S. G. Biedron,[1,2] M. Borland,[1] Y.-C. Chae,[1] R. J. Dejus,[1] P. K. Den Hartog,[1] B. Deriy,[1] M. Erdmann,[1] Y. I. Eidelman,[1] M. W. Hahne,[1] Z. Huang,[1] K.-J. Kim,[1] J. W. Lewellen,[1] Y. Li,[1] A. H. Lumpkin,[1] O. Makarov,[1] E. R. Moog,[1] A. Nassiri,[1] V. Sajaev,[1] R. Soliday,[1] B. J. Tieman,[1] E. M. Trakhtenberg,[1] G. Travish,[1] I. B. Vasserman,[1] N. A. Vinokurov,[3] X. J. Wang, G. Wiemerslage,[1] B. X. Yang[1]

VOLUME 88, NUMBER 10 PHYSICAL REVIEW LETTERS 11 MARCH 2002

Generation of GW Radiation Pulses from a VUV Free-Electron Laser Operating in the Femtosecond Regime

V. Ayvazyan,[4] N. Baboi,[7,16] I. Bohnet,[5] R. Brinkmann,[4] M. Castellano,[8] P. Castro,[4] L. Catani,[10] S. Choroba,[4] A. Cianchi,[10] M. Dohlus,[4] H. T. Edwards,[6] B. Faatz,[4] A. A. Fateev,[13] J. Feldhaus,[4] K. Flöttmann,[4] A. Gamp,[4] T. Garvey,[14] H. Genz,[3] Ch. Gerth,[4] V. Gretchko,[11] B. Grigoryan,[19] U. Hahn,[4] C. Hessler,[3] K. Honkavaara,[4] M. Hüning,[17] R. Ischebeck,[17] M. Jablonka,[1] T. Kamps,[5] M. Körfer,[4] M. Krassilnikov,[2] J. Krzywinski,[12] M. Liepe,[7] A. Liero,[17] T. Limberg,[4] H. Loos,[3] M. Luong,[1] C. Magne,[1] J. Menzel,[17] P. Michelato,[9] M. Minty,[4] U.-C. Müller,[4] D. Nölle,[4] A. Novokhatski,[2] C. Pagani,[9] F. Peters,[4] J. Pflüger,[4] P. Piot,[4] L. Plucinski,[7] K. Rehlich,[4] I. Reyzl,[4] A. Richter,[3] J. Rossbach,[4] E. L. Saldin,[4] W. Sandner,[15] H. Schlarb,[7] G. Schmidt,[4] P. Schmüser,[7] J. R. Schneider,[4] E. A. Schneidmiller,[4] H.-J. Schreiber,[5] S. Schreiber,[4] D. Sertore,[9] S. Setzer,[2] S. Simrock,[4] R. Sobierajski,[4,18] B. Sonntag,[7] B. Steeg,[4] F. Stephan,[5] K. P. Sytchev,[13] K. Tiedtke,[4] M. Tonutti,[17] R. Treusch,[4] D. Trines,[4] D. Türke,[17] V. Verzilov,[8] R. Wanzenberg,[4] T. Weiland,[2] H. Weise,[4] M. Wendt,[4] I. Will,[15] S. Wolff,[4] K. Wittenburg,[4] M. V. Yurkov,[13,*] and K. Zapfe[4]

VOLUME 88, NUMBER 20 PHYSICAL REVIEW LETTERS 20 MAY 2002

Experimental Characterization of Nonlinear Harmonic Radiation from a Visible Self-Amplified Spontaneous Emission Free-Electron Laser at Saturation

A. Tremaine,[1] X. J. Wang,[2] M. Babzien,[2] I. Ben-Zvi,[2] M. Cornacchia,[3] H.-D. Nuhn,[3] R. Malone,[2] A. Murokh,[1] C. Pellegrini,[1] S. Reiche,[1] J. Rosenzweig,[1] and V. Yakimenko[2]

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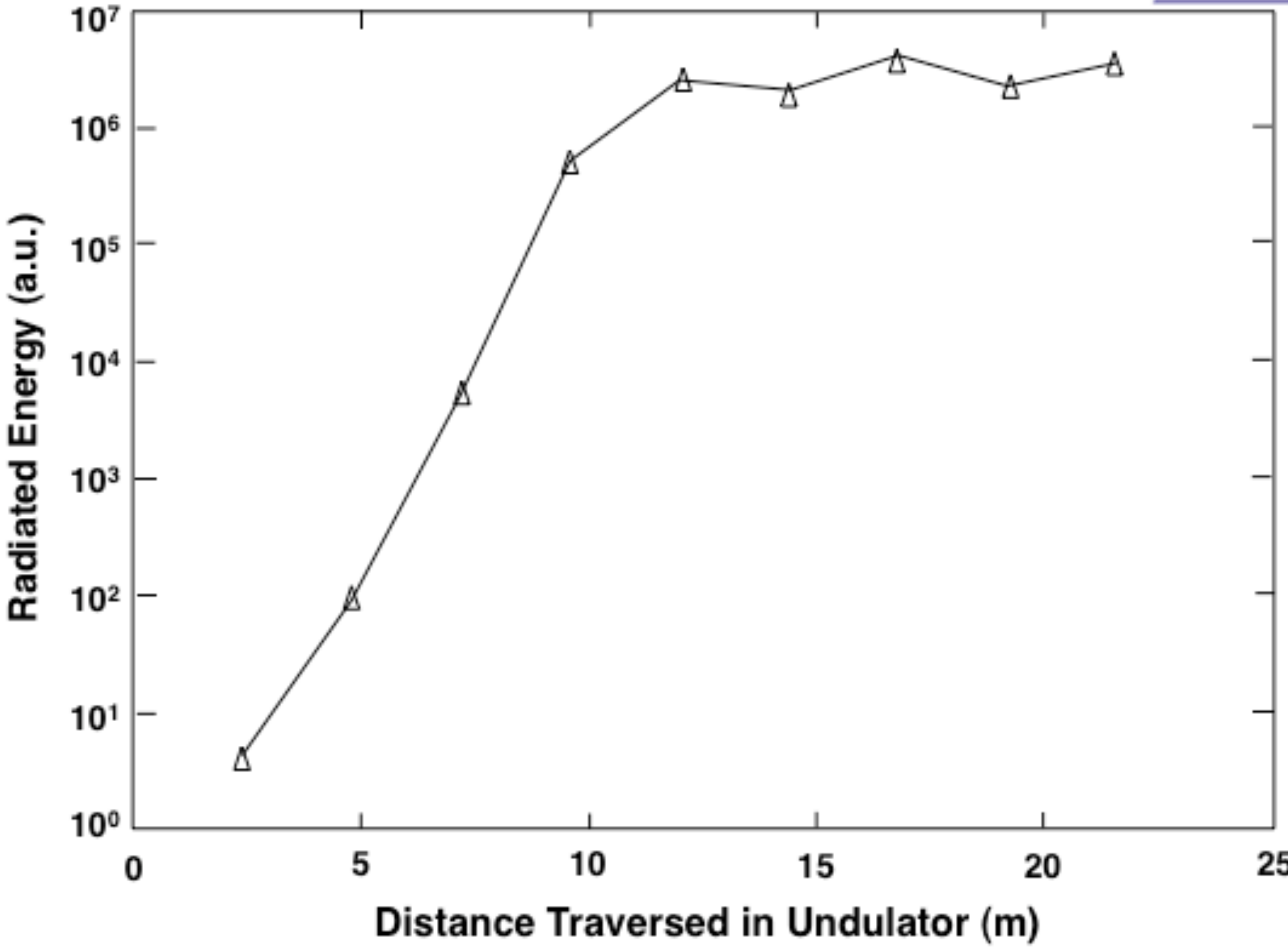
(Received 20 September 2001; published 3 May 2002)

A compact free-electron laser for generating coherent radiation in the extreme ultraviolet region

nature photonics | VOL 2 | SEPTEMBER 2008

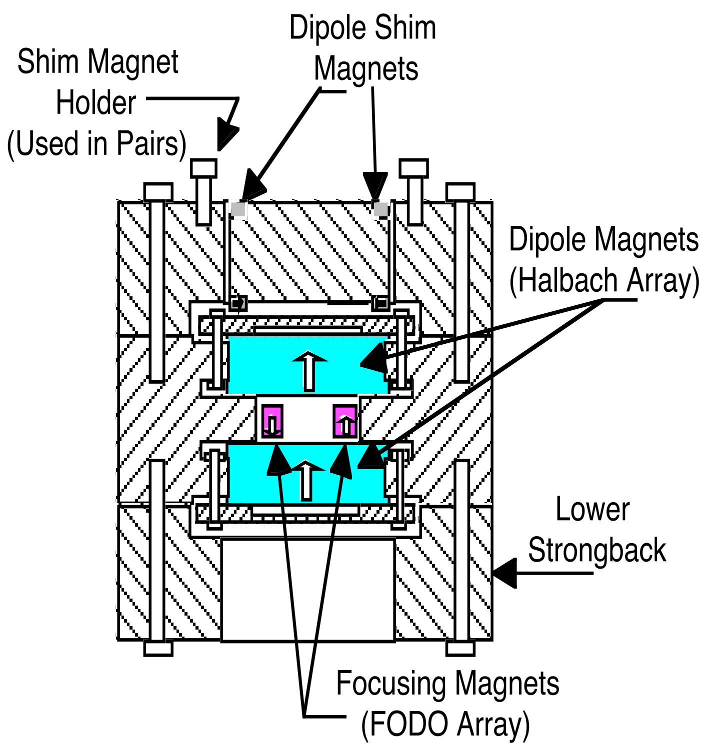
LEUTL Gain Curve @ 530 nm on March 10, 2001

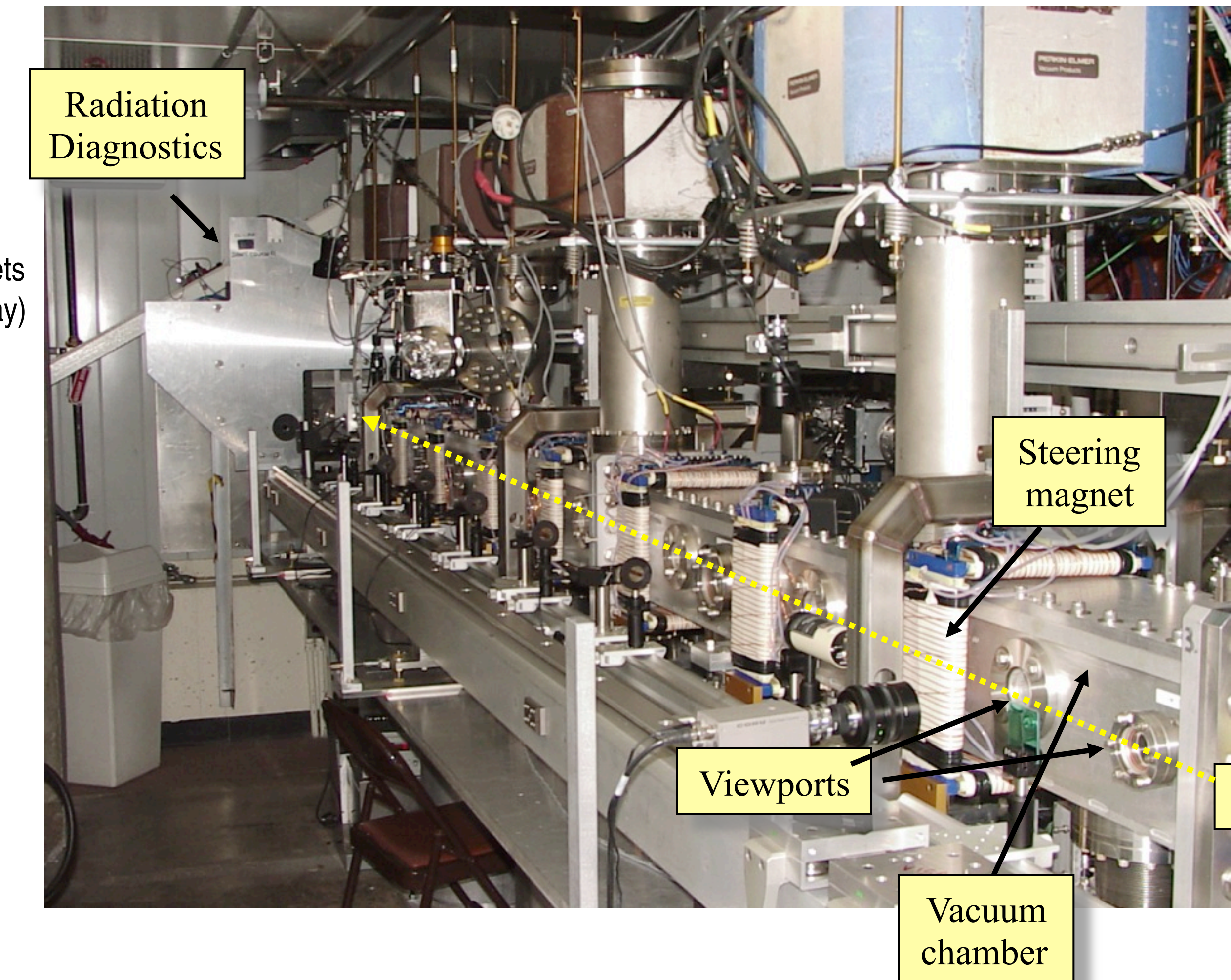
ADVANCED PHOTON SOURCE



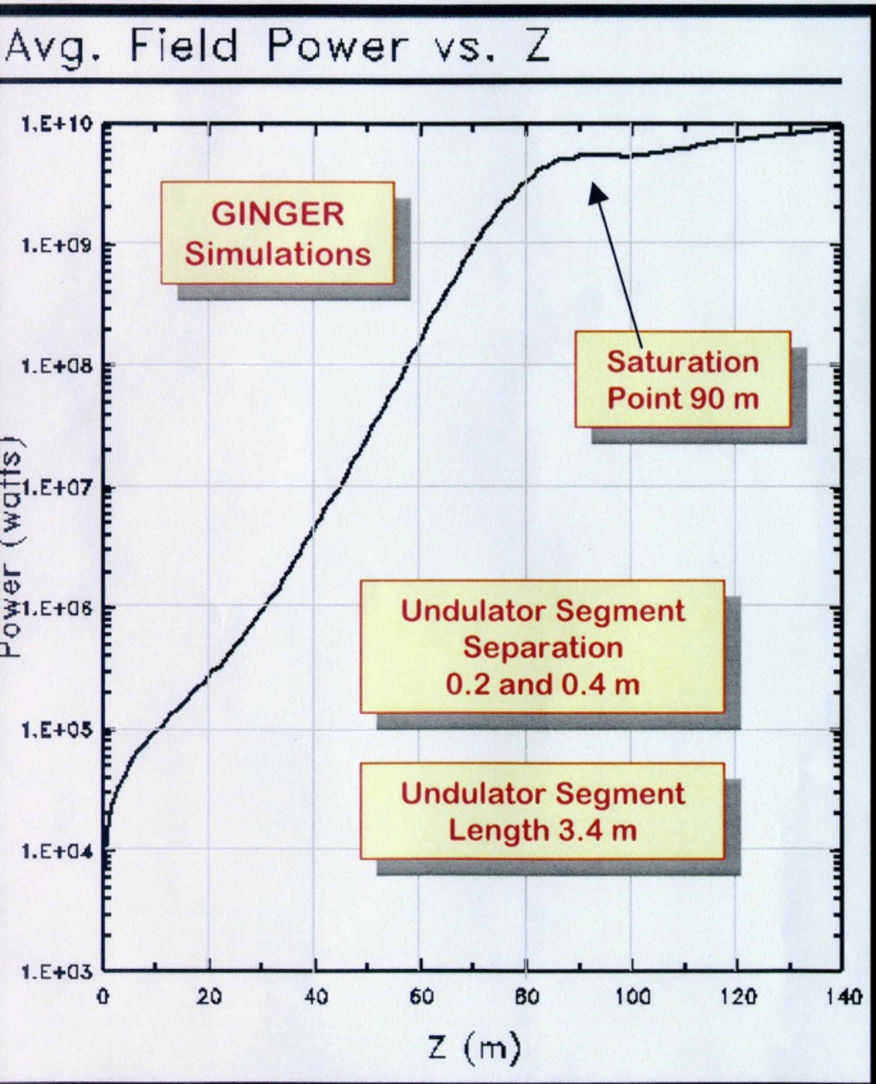
S. Milton, et al, Science, 292, 2037-2041(2001).

VISA Experimental setup





LCLS Performance with VISA Beam Quality

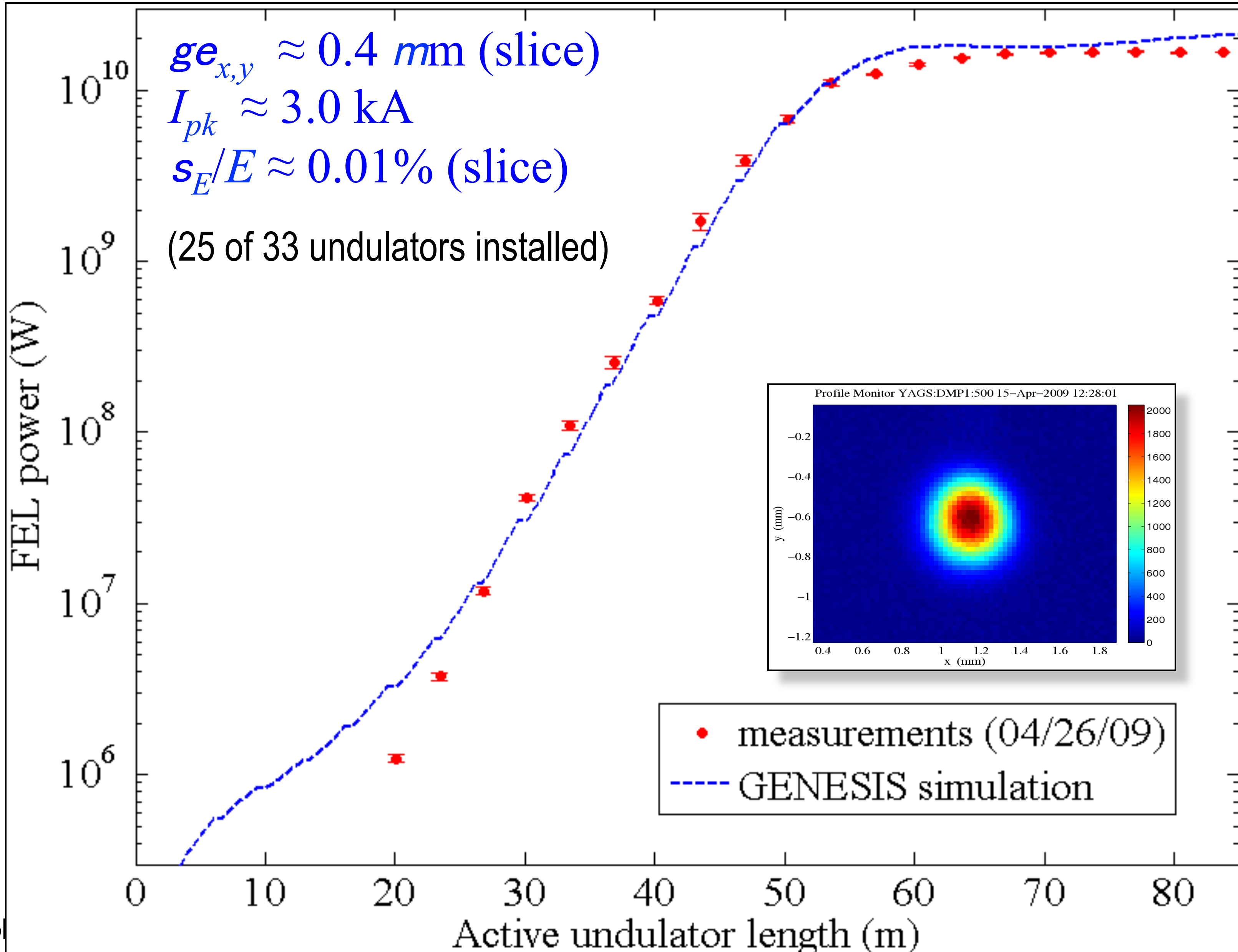


Estimated Slice Emittance:	0.8 mm mrad
Average Charge:	170 pC
RMS Gun Bunch Length:	900 fs
Bunch Compression Factor:	23
RMS Bunch Length at Undulator:	40 fs
Peak Current:	1700 A
Energy Spread:	1×10^{-4}
Wavelength	0.15 nm
Gain Length	4.4 m
Saturation Length:	90 m
Peak SASE Power:	7 GW

Results of Simulations with the Computer Code GINGER using Electron Beam Qualities measured at VISA. The linac bunch compression factor is 23, which is smaller than the present design value.

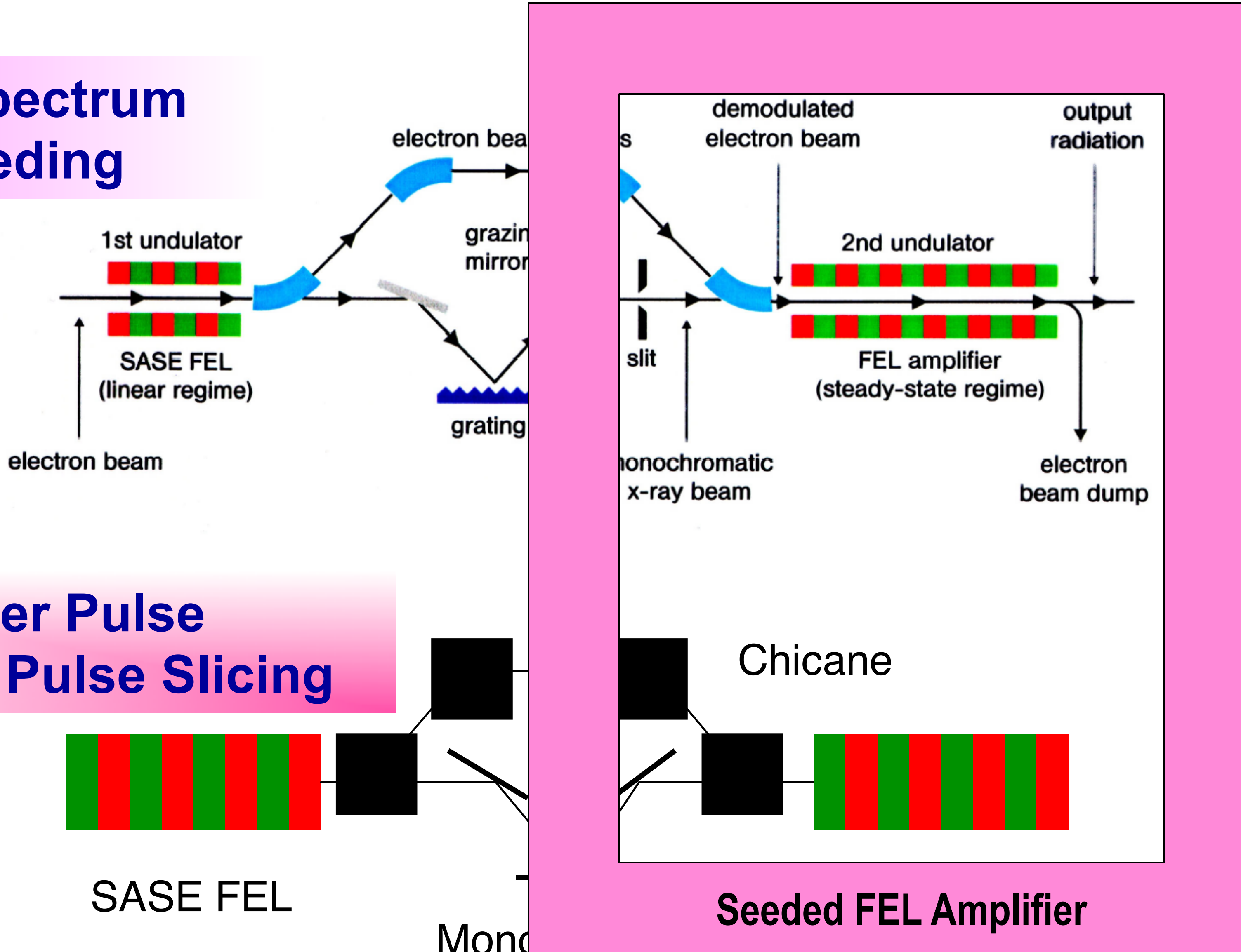
This set of parameters can be further optimized and other working points will be certainly developed when LCLS will operate.

Undulator Gain Length Measurement at 1.5 Å: 3.3 m



Beyond SASE - Next Generation XFEL

Narrow Spectrum
Self-seeding

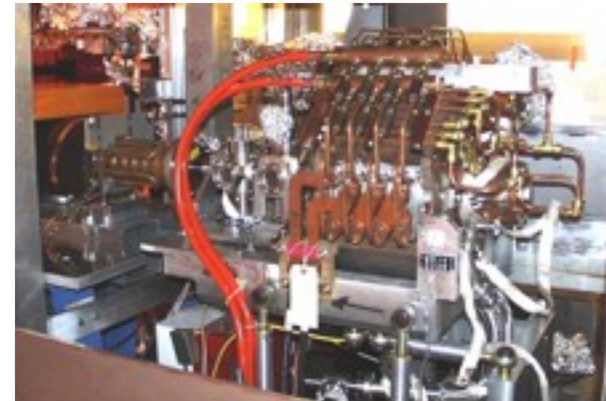


Shorter Pulse
Two-stage Pulse Slicing

NSLS SDL Facility

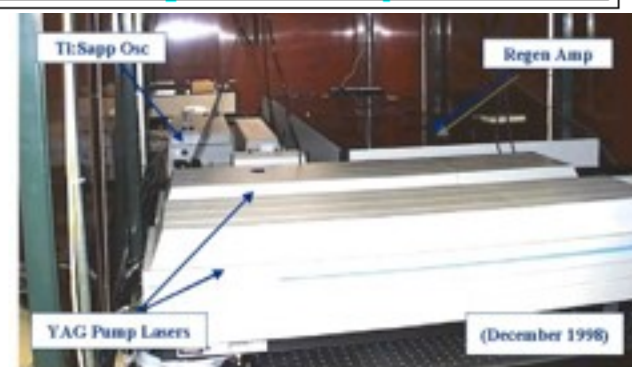
300 MeV S-Band Linac

BNL Photoinjector IV



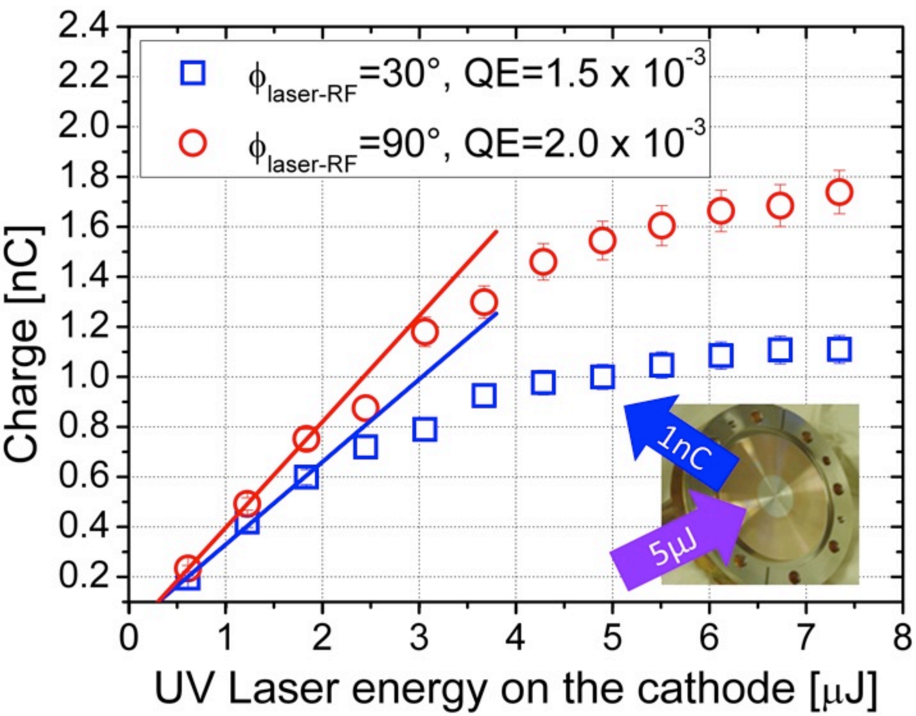
10 m NISUS Wiggler

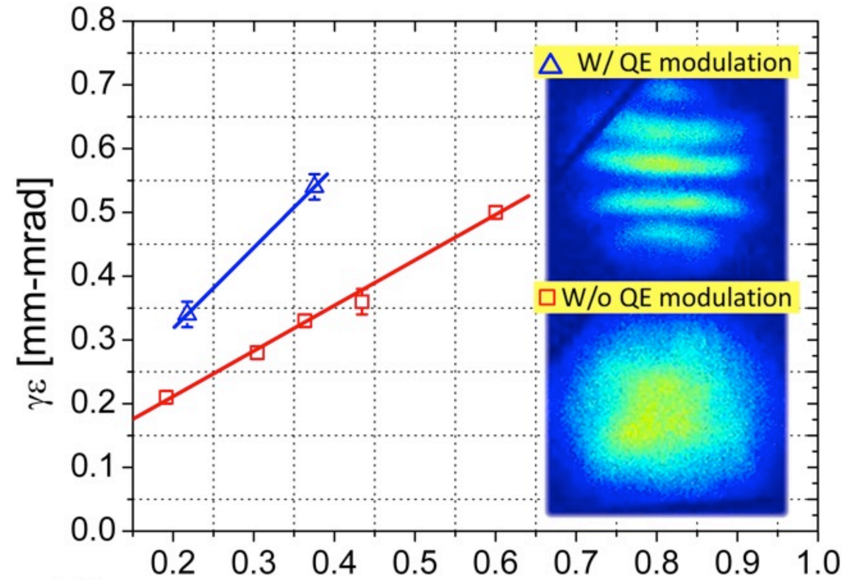
Chicane Compressor

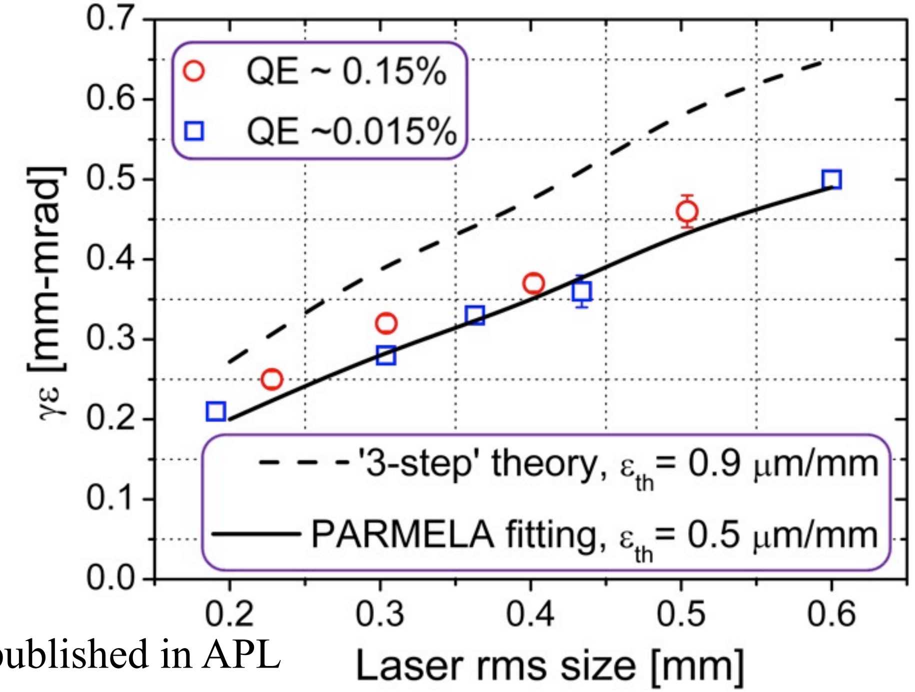


Titanium Sapphire Laser

High-brightness e^- R&D

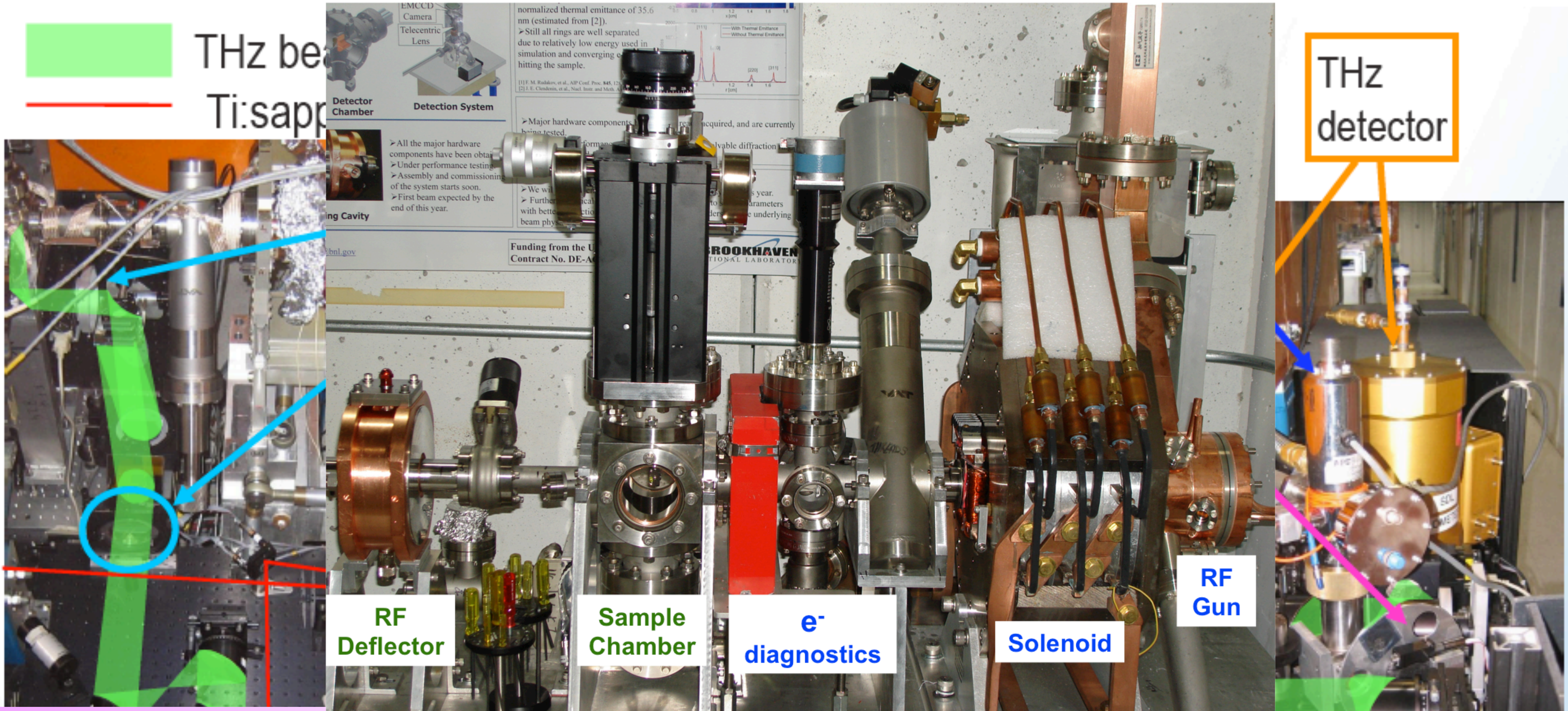






H. Qian et al, to be published in APL

Ultrafast Science @ SDL



A Platform for Ultrafast Science

- Strongly correlated electron materials.
- Ultrafast Phase Transitions
- Lattice Vibration Dynamics.
- Warm Dense Matter.
- Photo-reaction in Gas Phase.

Next Generation e^- Source R&D

- Thermal emittance studies.
- Beam dynamics for space charge dominated beam.
- Next generation BNL RF gun R&D.

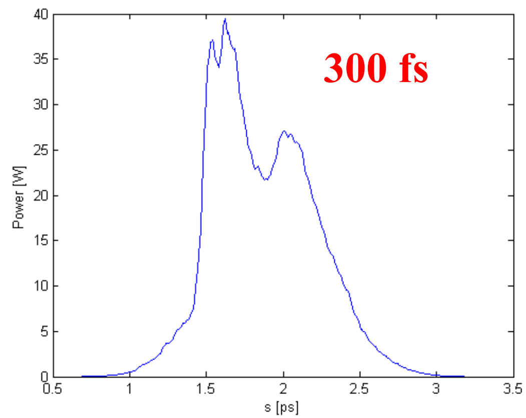
Experimental Demonstration of Coherent SASE @ the NSLS SDL

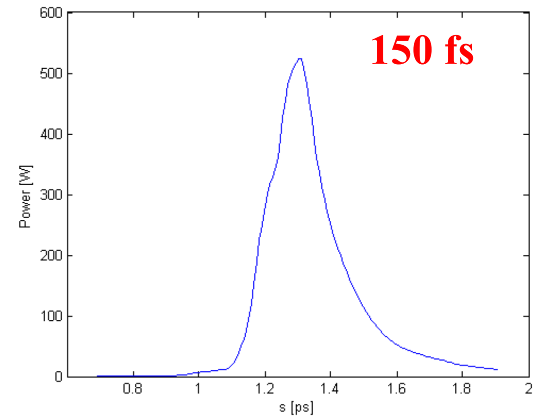
700 – 800 nm Coherent SASE:

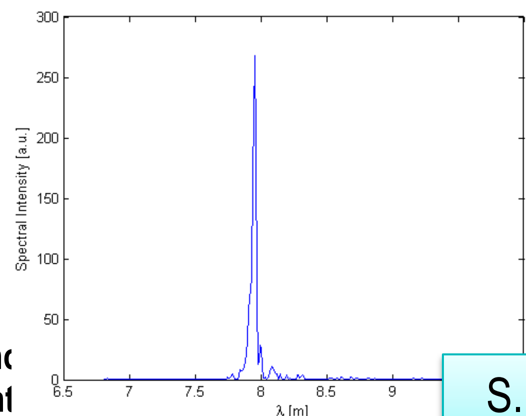
- Validate coherent SASE physics.
- Verified the short pulse generation.
- Sophisticated optical diagnostics.

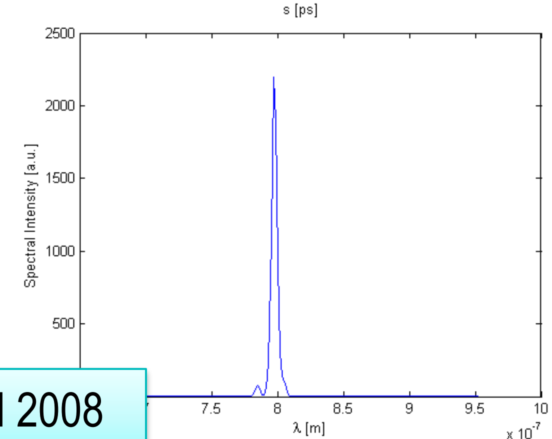
$$\sigma_{b,ss} < 2\pi L_{c,1D} = \frac{\lambda_r}{2\sqrt{3}\rho_{1D}}$$

Gun + Chicane



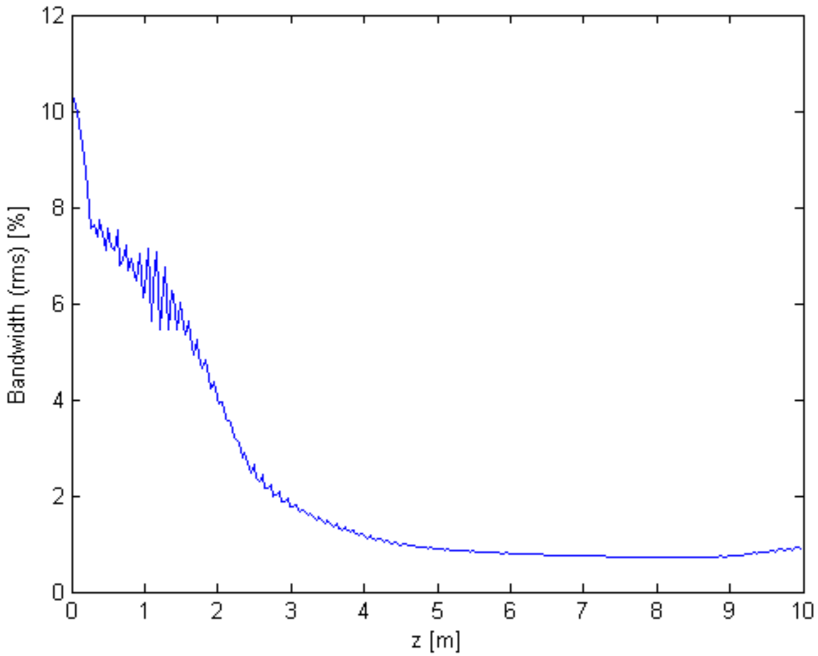


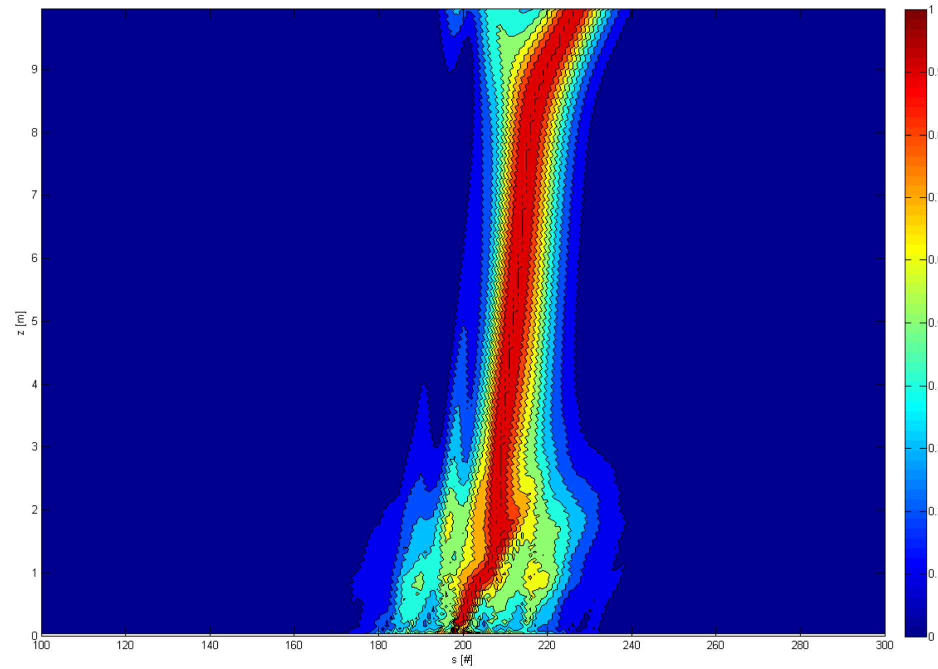




S. Reiche, ELBA/NIM 2008

Expected Coherent SASE Performance

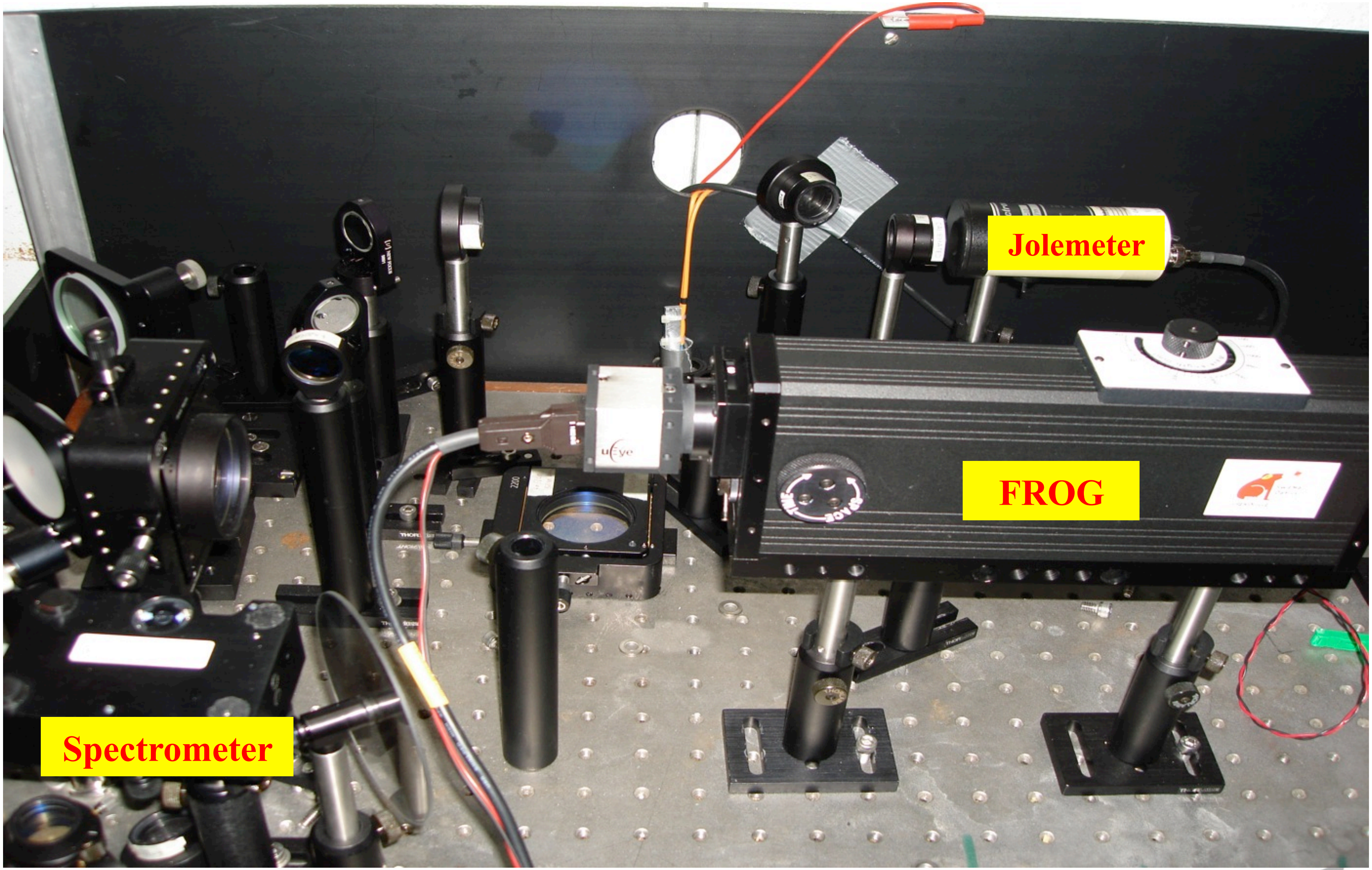




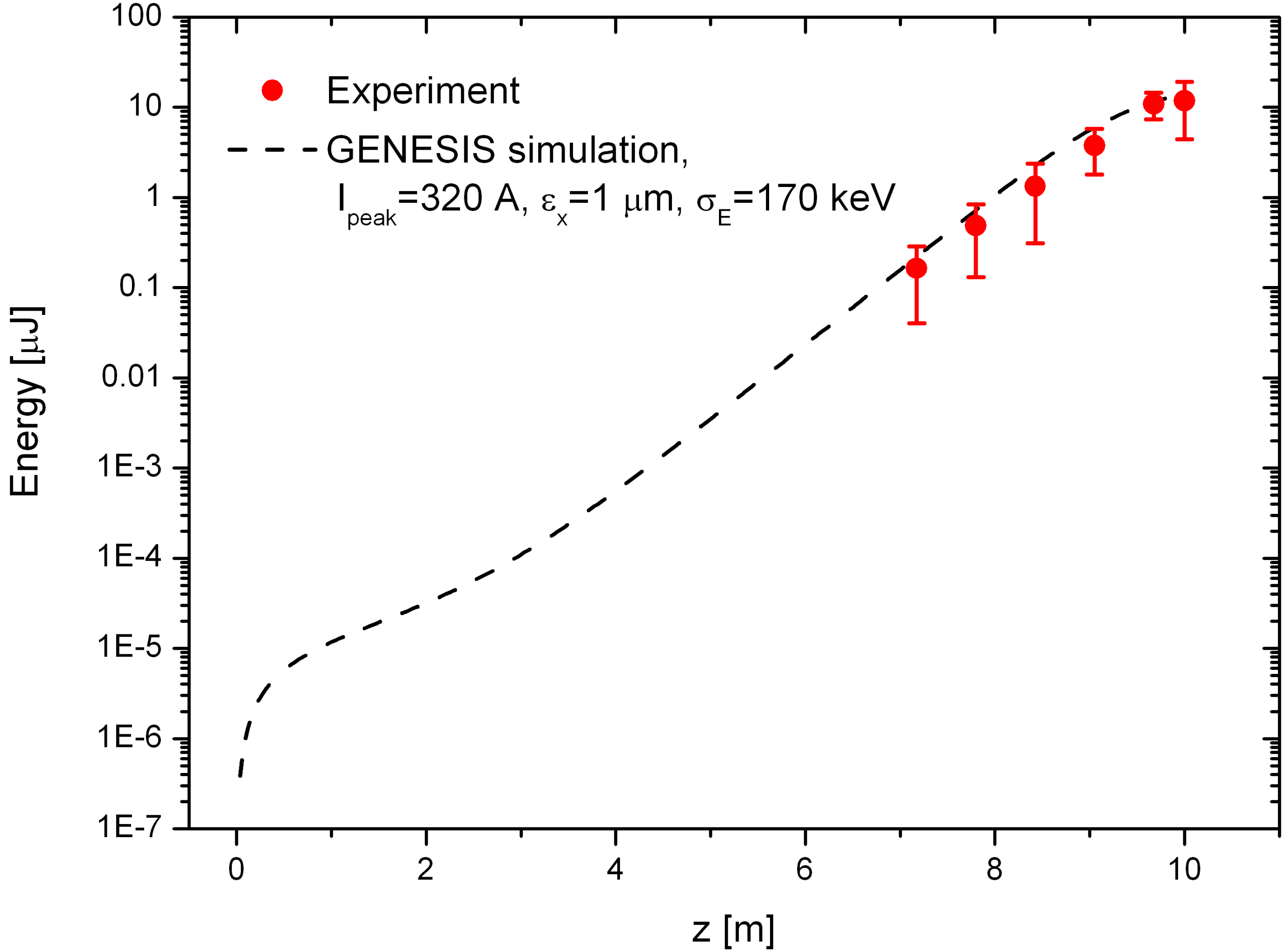
e⁻ parameters:
Q: 100 pC
σ_z (rms): 120 fs
ε: < 2 mm-mrad

Coherent SASE:
- λ : 700 – 800 nm
- σ_z (FWHM): 100 fs
- E: ~ 10 μJ

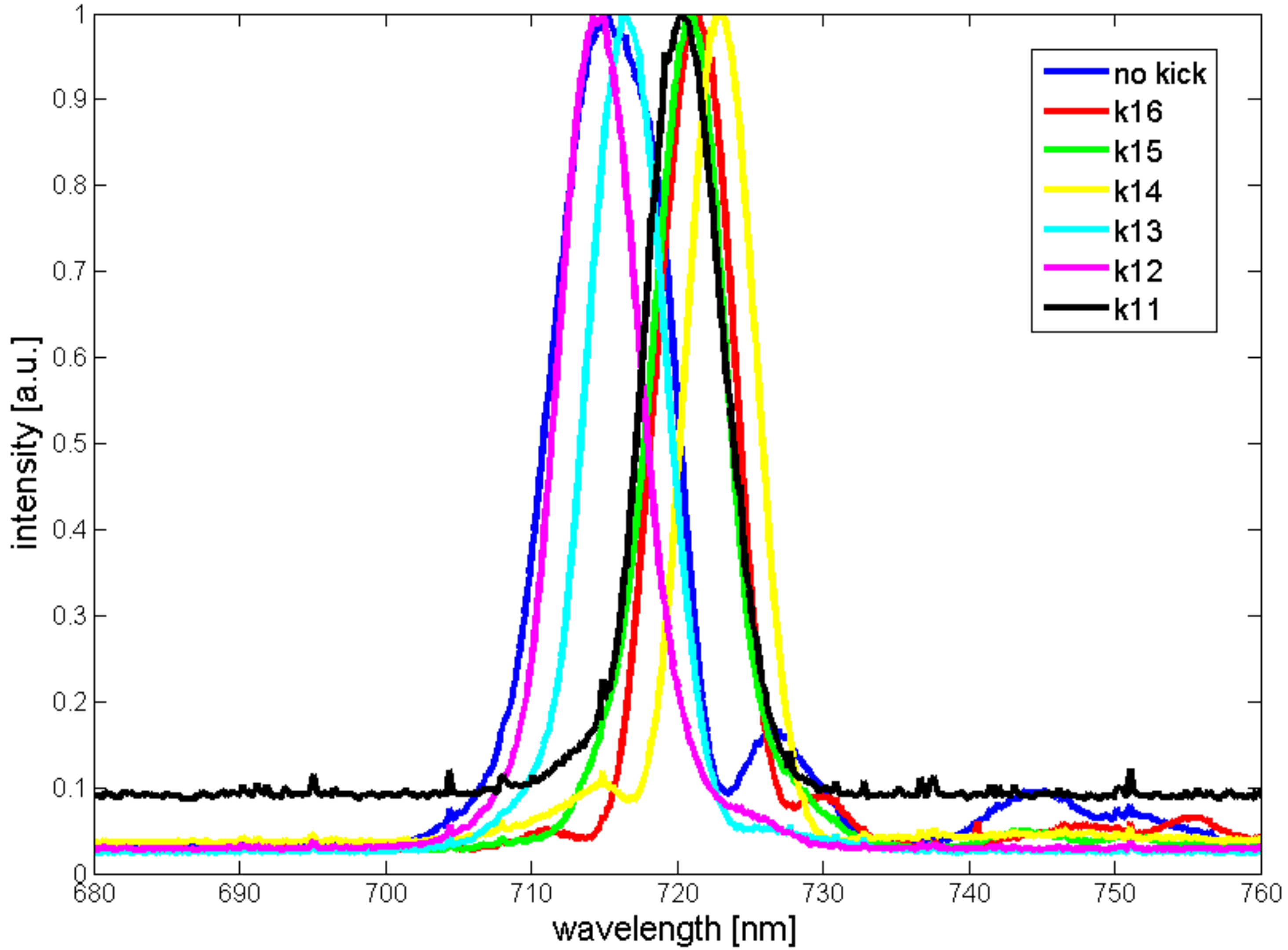
Experimental Set-up



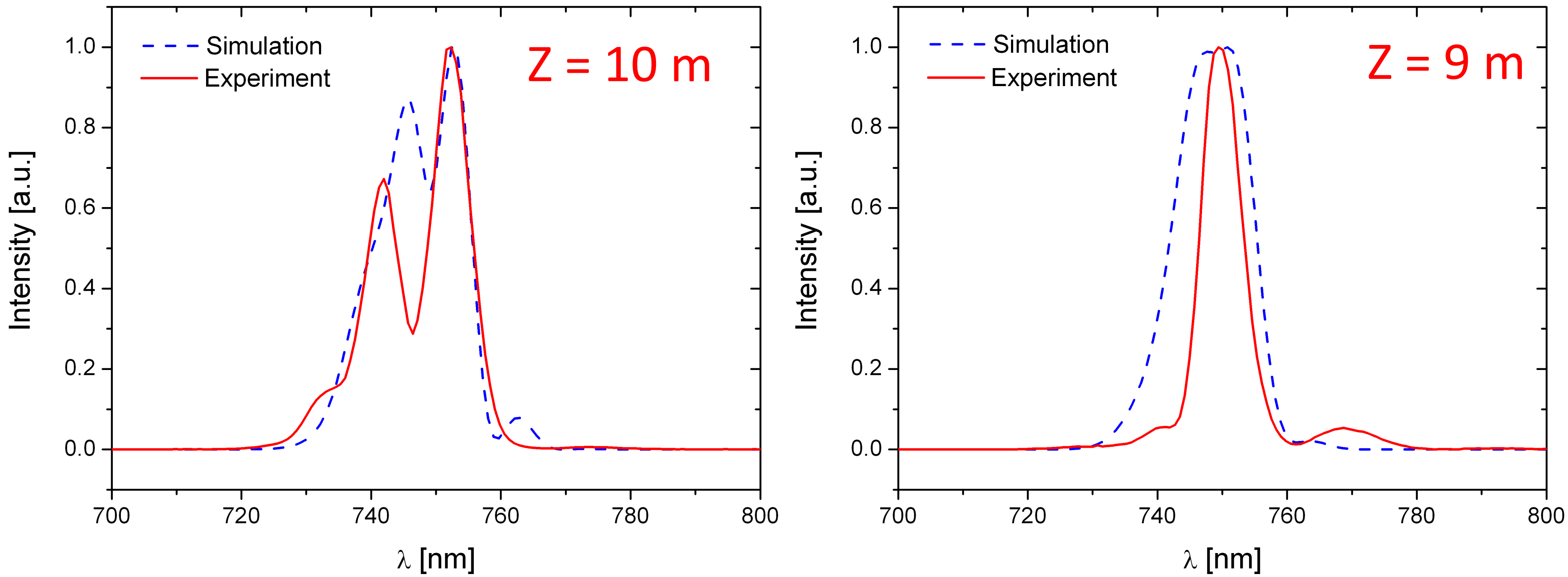
Single spike SASE



Coherent SASE Spectral Evolution

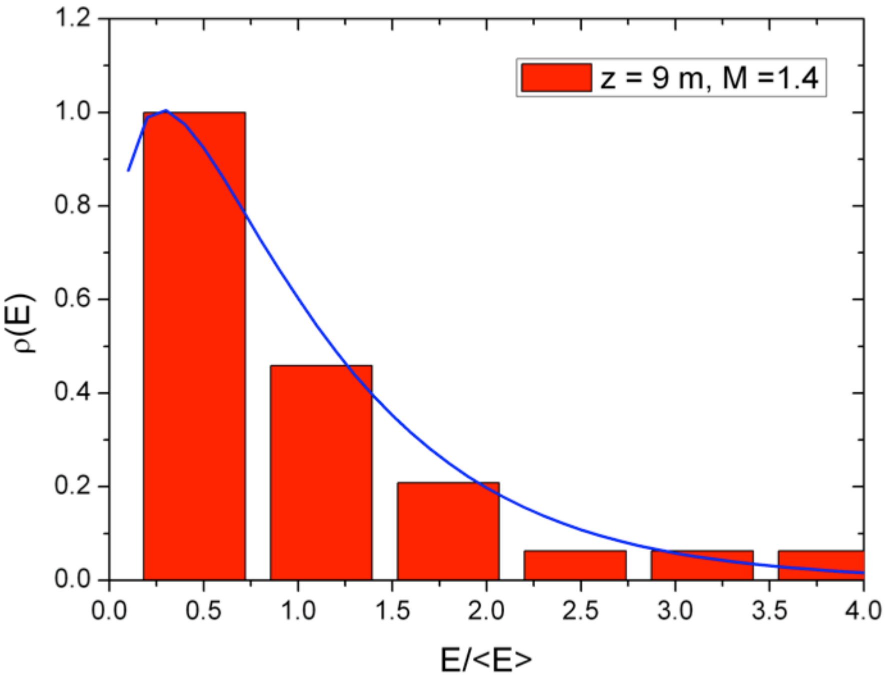


Single spike SASE

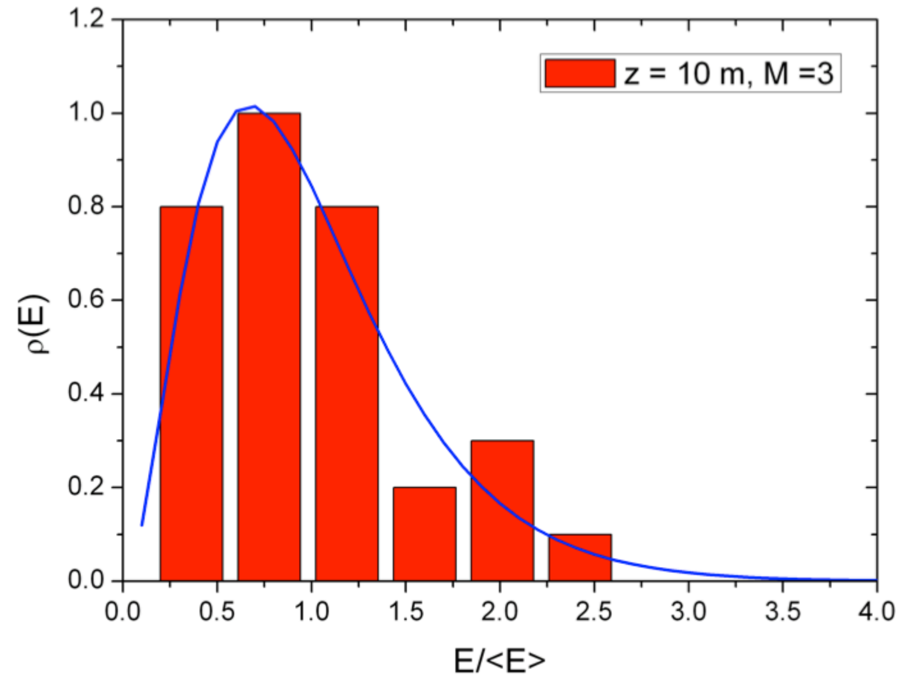


Spectral Before and After the Saturation.

Single spike SASE - Mode

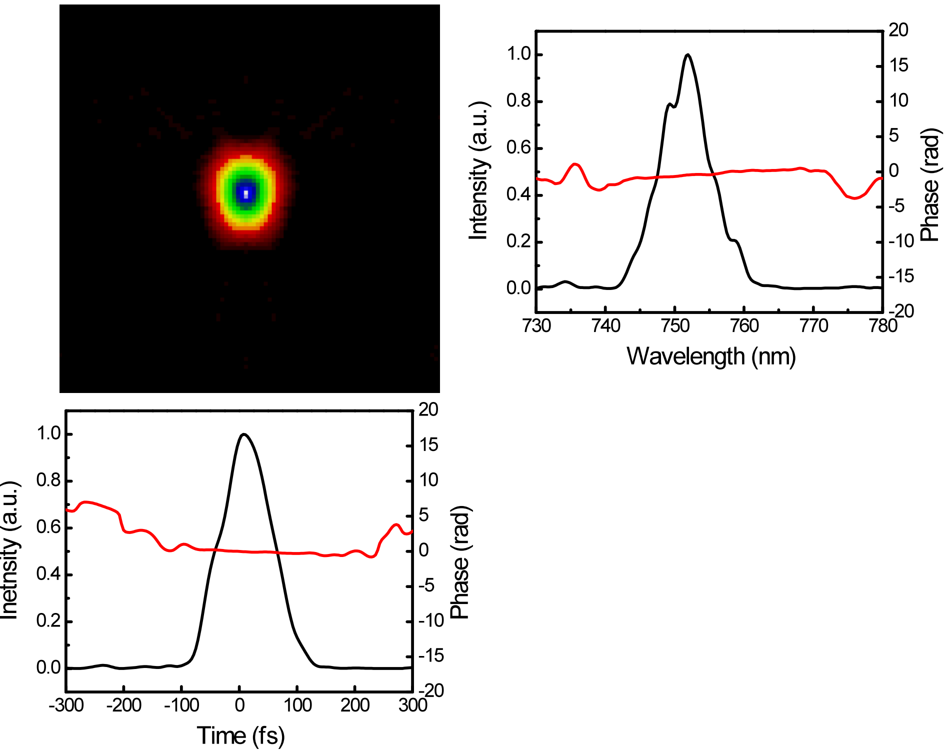


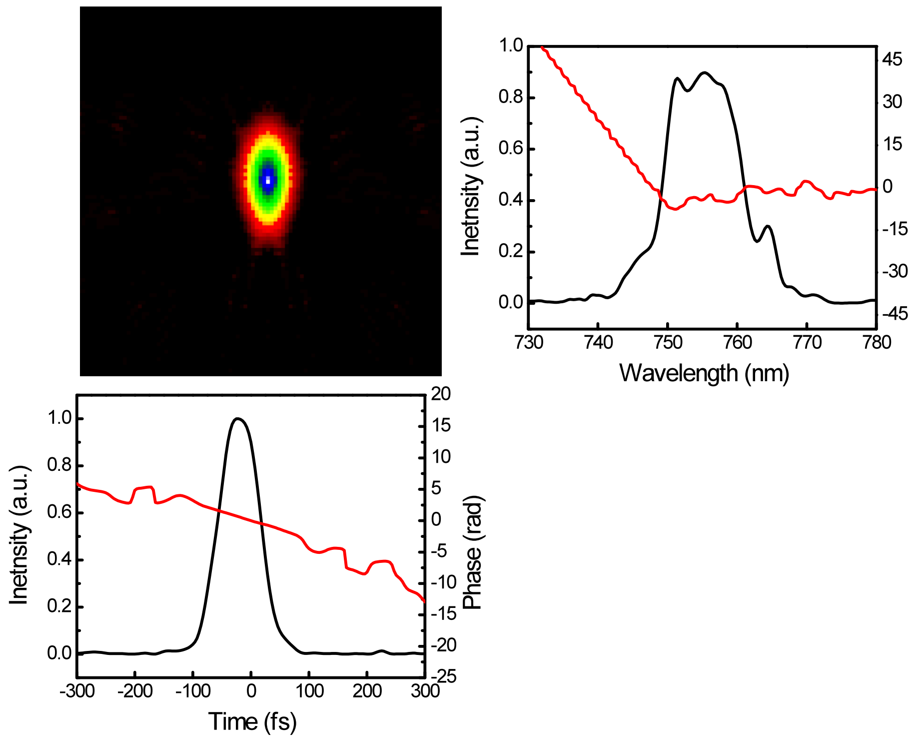
Before Saturation



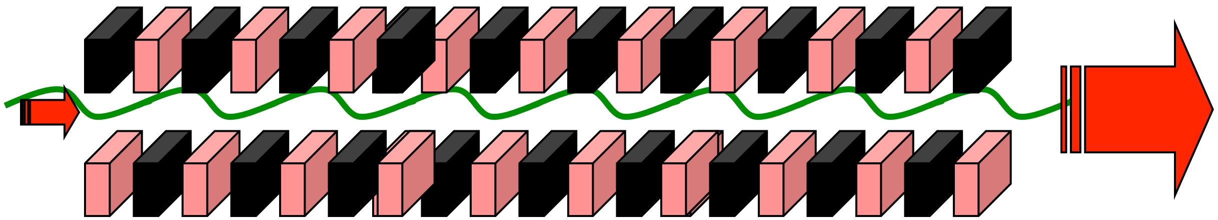
After Saturation

Transform Limited SASE Observation

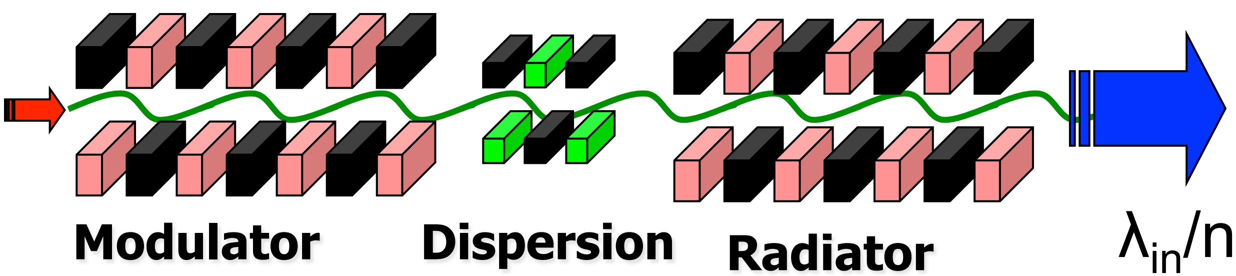




Laser Seeded FEL Amplifiers

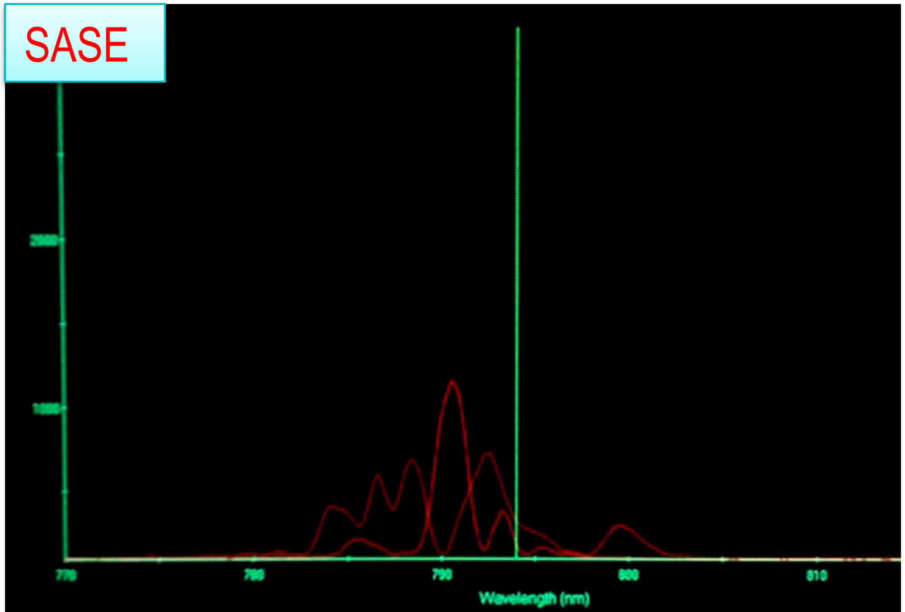


- "First Operation of a Free Electron Laser", D.A.G. Deacon et al., PRL 38, 892 (1977).
- "Microwave Radiation from a High Gain Free Electron Laser Amplifier", T.J. Orzechowski et al, PRL 54, 889 (1985).
- X.J. Wang et al., APL 91, 181115 (2007).
- G. Lambert et al., Nature Physics 4, 296 (2008).

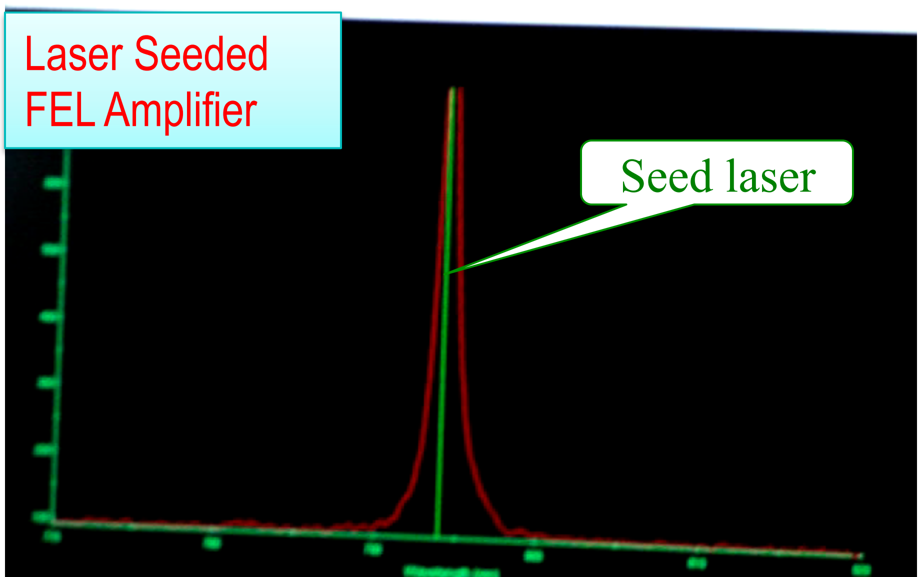


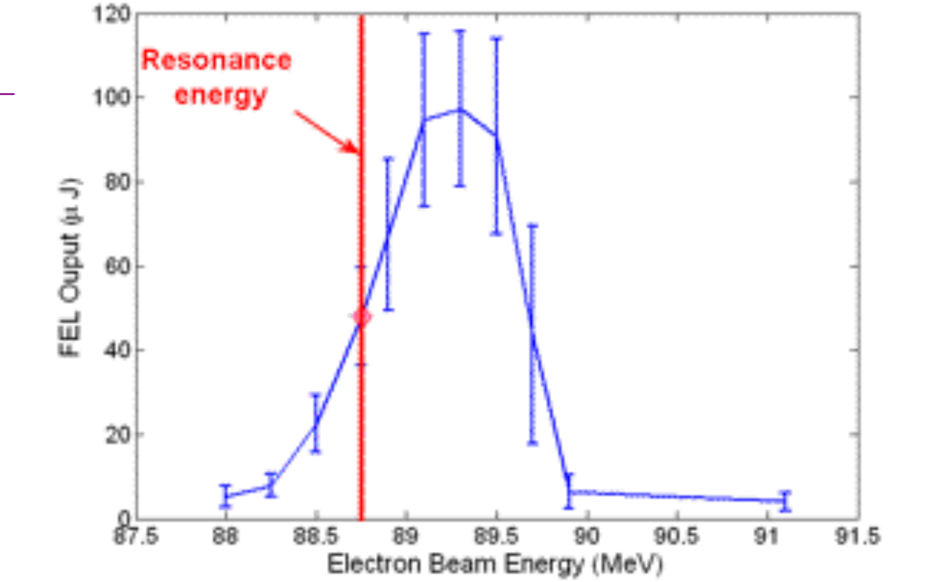
- "High-Gain Harmonic-Generation Free-Electron Laser", L.H. Yu et al, Science **289**, 932 (2000).
- "First Ultraviolet High Gain Harmonic Generation Free Electron Laser", L.H. Yu et al, PRL 91, 074801-1 (2003).
- "The First Lasing of 193 nm SASE, 4th Harmonic HGHG & ESASE at the NSLS SDL", X.J. Wang et al, Proc FEL06, 18 (2006).
- Demonstration of the Echo-Enabled Harmonic Generation Technique for Short-Wavelength Seeded Free Electron Lasers, D.Xiang *et al. Phys. Rev. Lett*. **105,** 114801 (2010).

SDL laser seeded FEL Amplifier Detuning Experiment



Wavelength (nm)





Detuning: Electron beam energy deviates from the resonance:

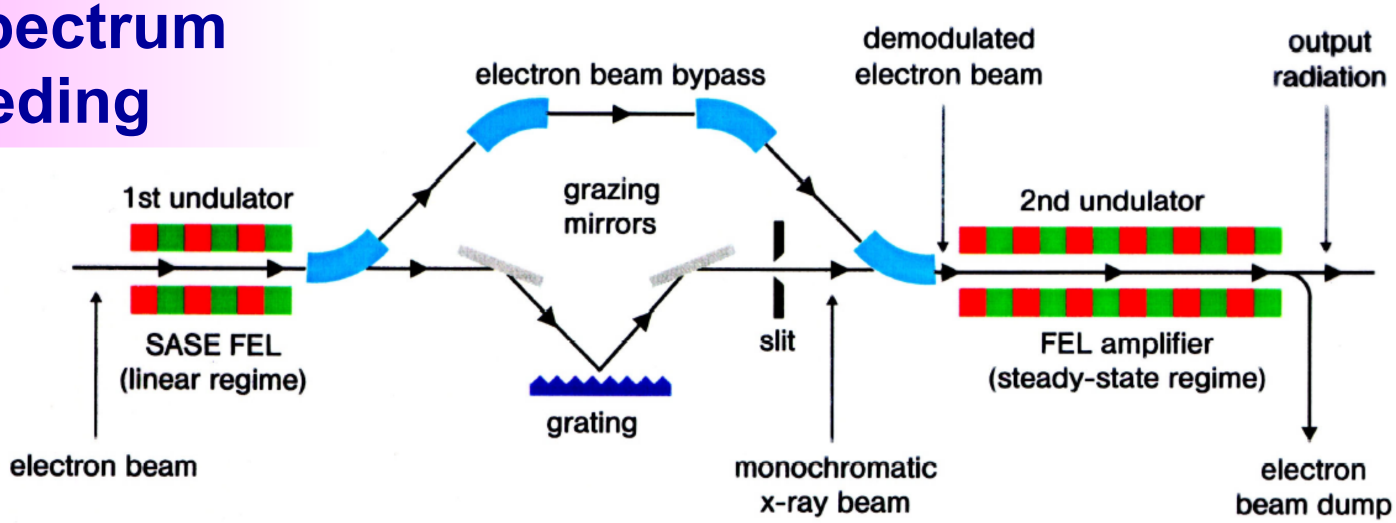
•FEL spectral is stable.

•FEL efficiency mdoubled.

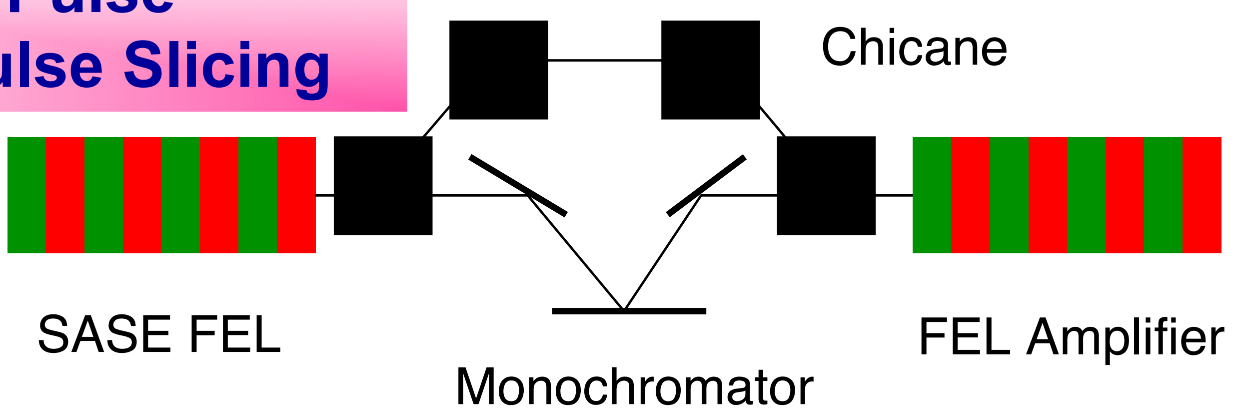
X.J. Wang *et al.*, APL **91**, 181115 (2007).

Beyond SASE - Next Generation XFEL

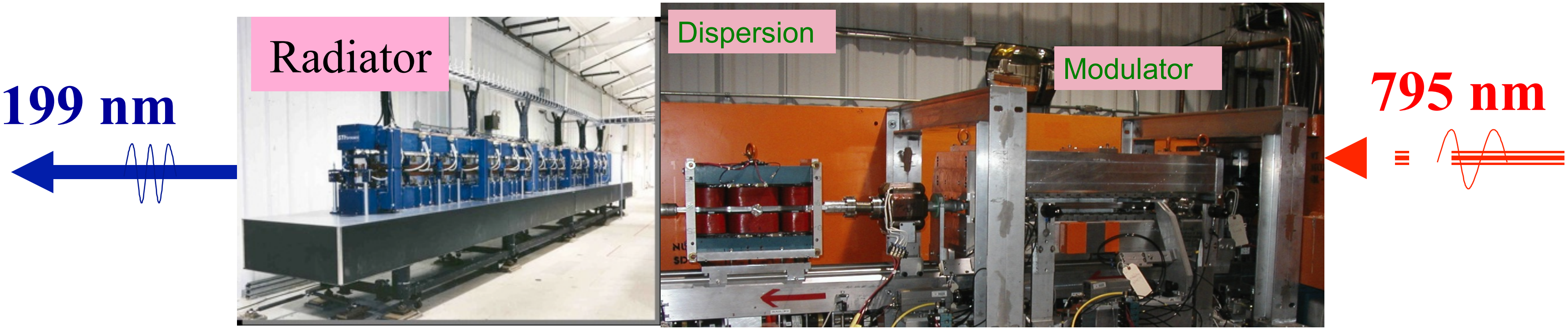
Narrow Spectrum Self-seeding

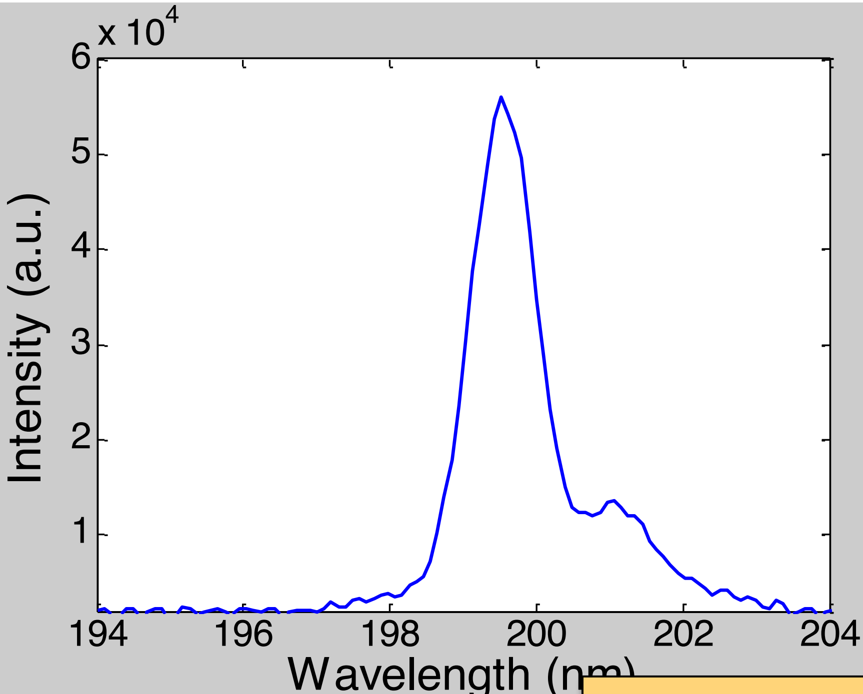


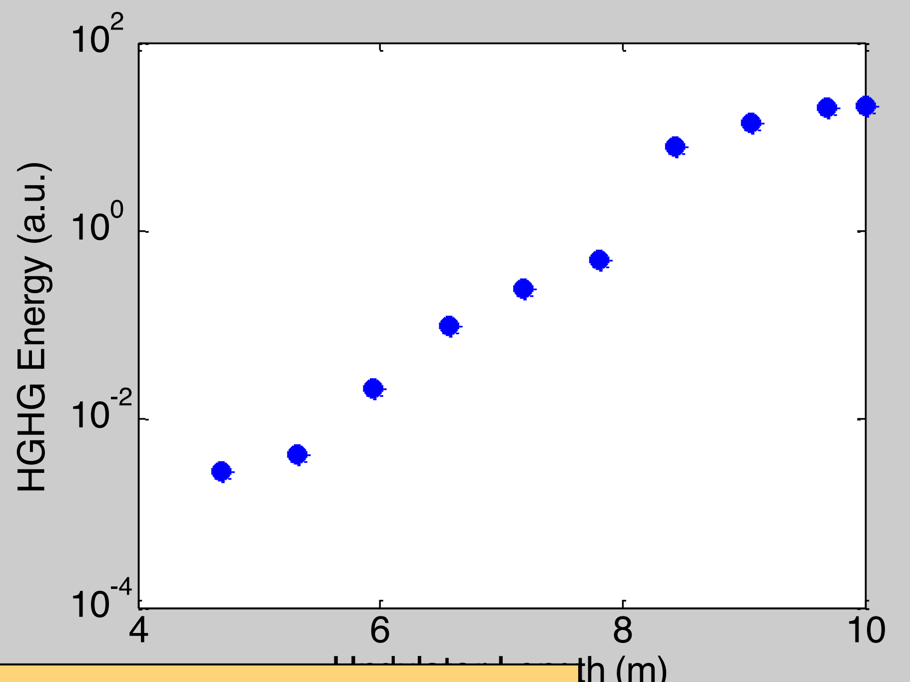
Shorter Pulse Two-stage Pulse Slicing



4th Harmonic HGHG @ NSLS SDL

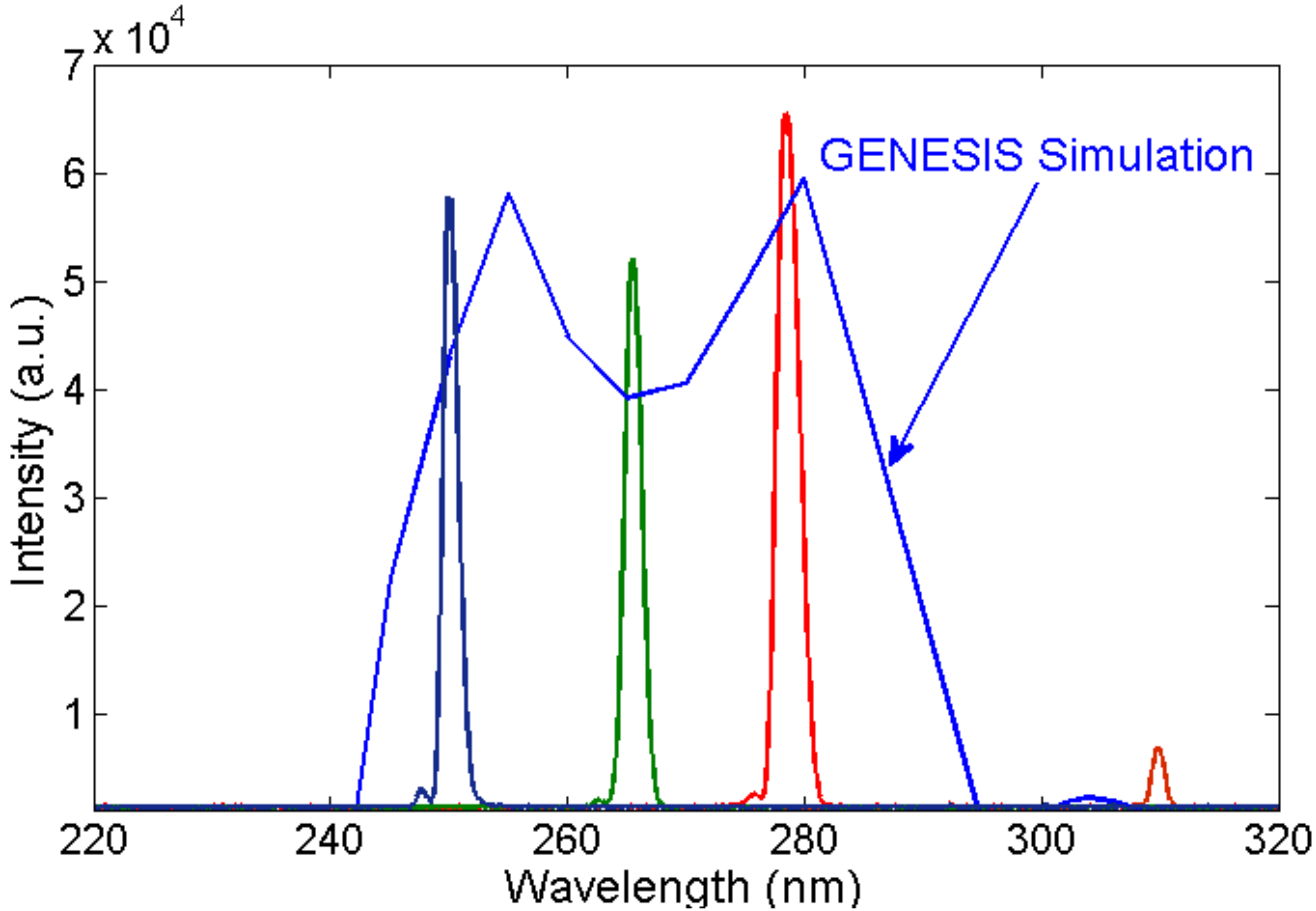






X.J. Wang, et. al. Proc. of FEL 2006, p.18 (2006).

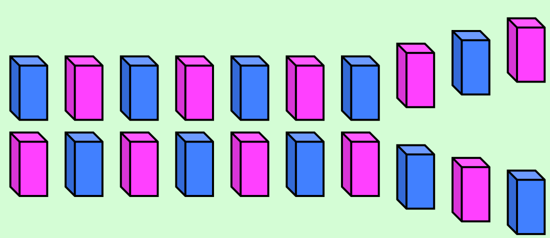
Harmonic FEL Spectral Tuning



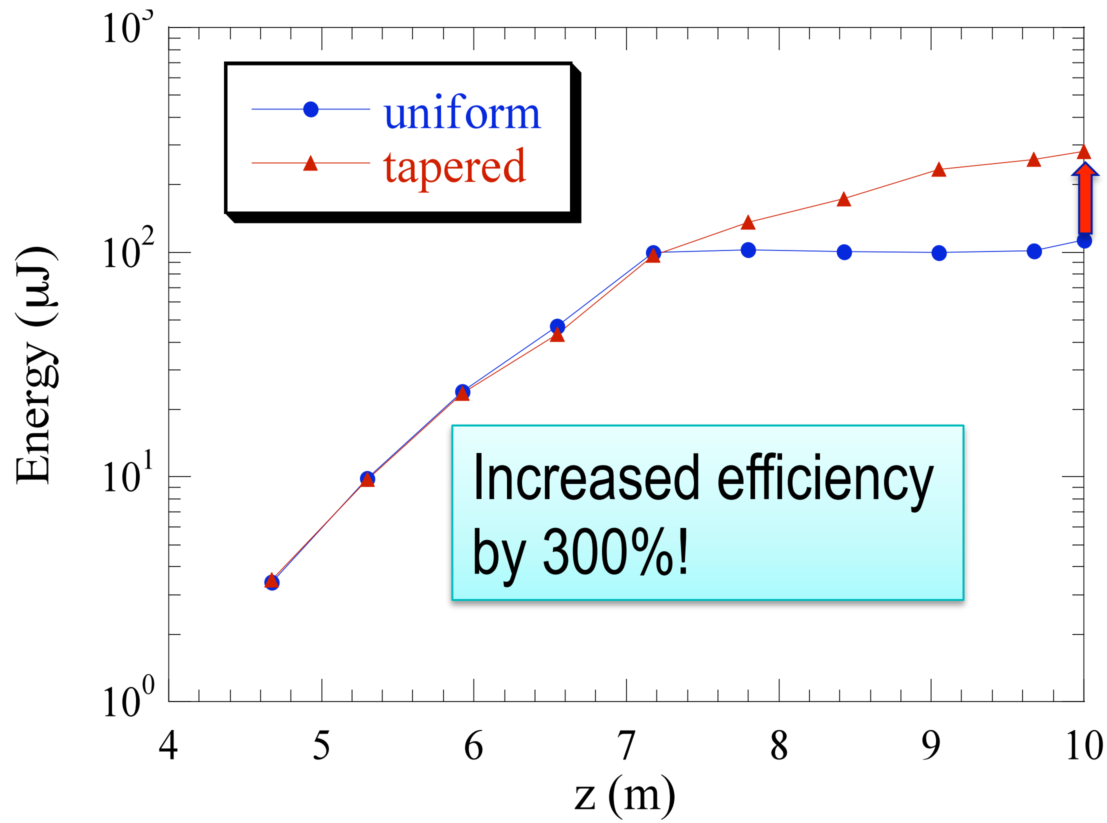
~ 20% wavelength tuning was experimentally demonstrated.

Beyond Saturation: Tapering for Efficiency and Coherence Preservation

Tapering is one of the key technologies to improve and preserve the FEL performance.

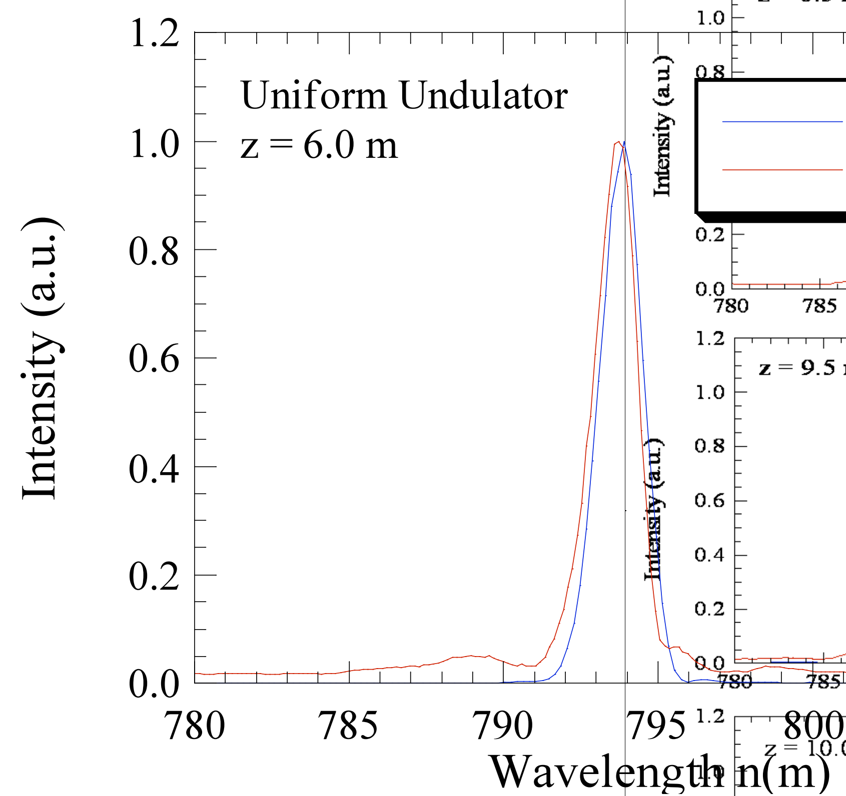


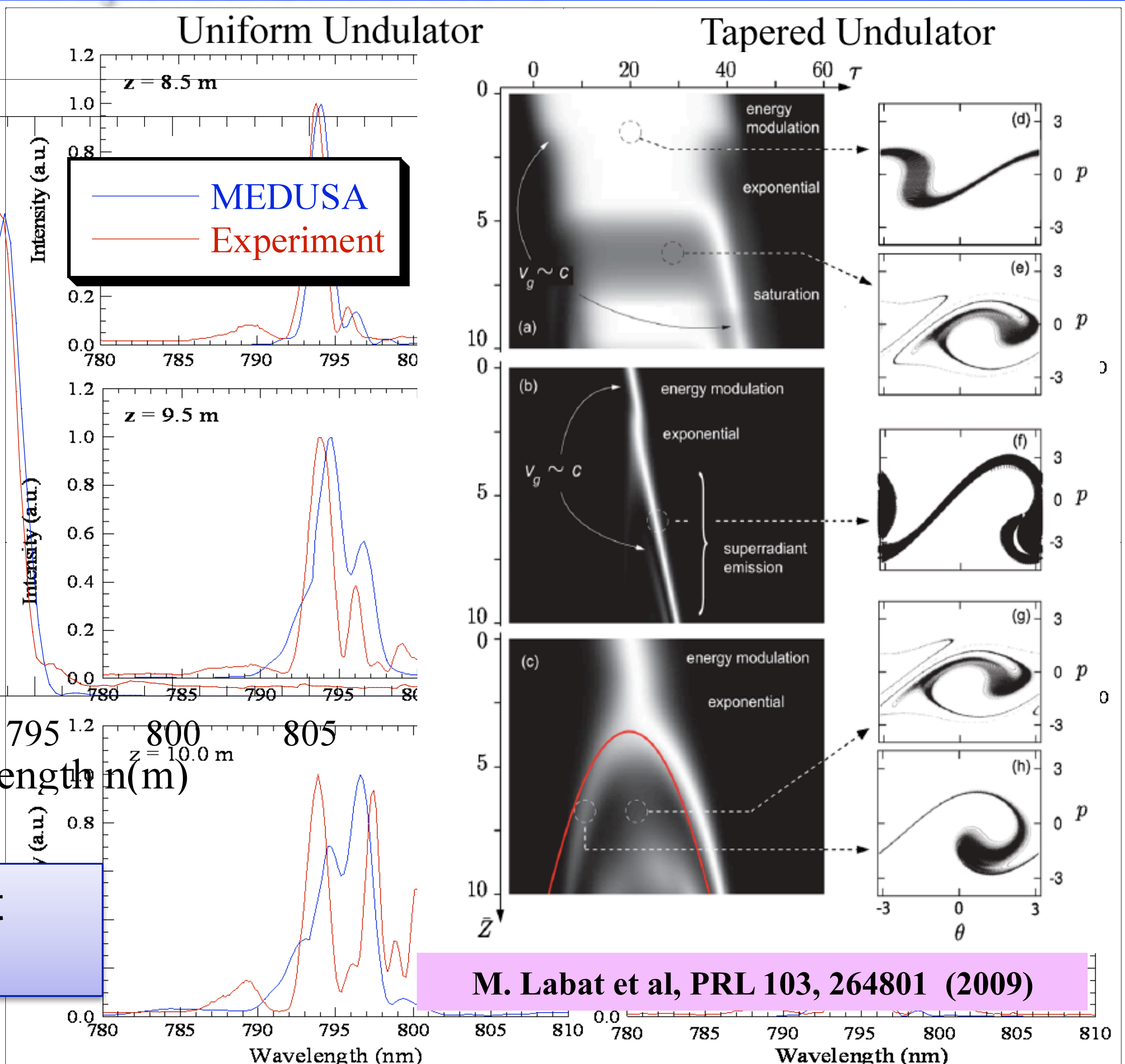
NISUS Can Be Tapered!



X.J. Wang *et al*, PRL **103**, 154801 (2009).

FEL Spectrum: Experiment vs. Simulation for Uniform & Tapered Undulators





Agreement between experiment & simulation is very good.

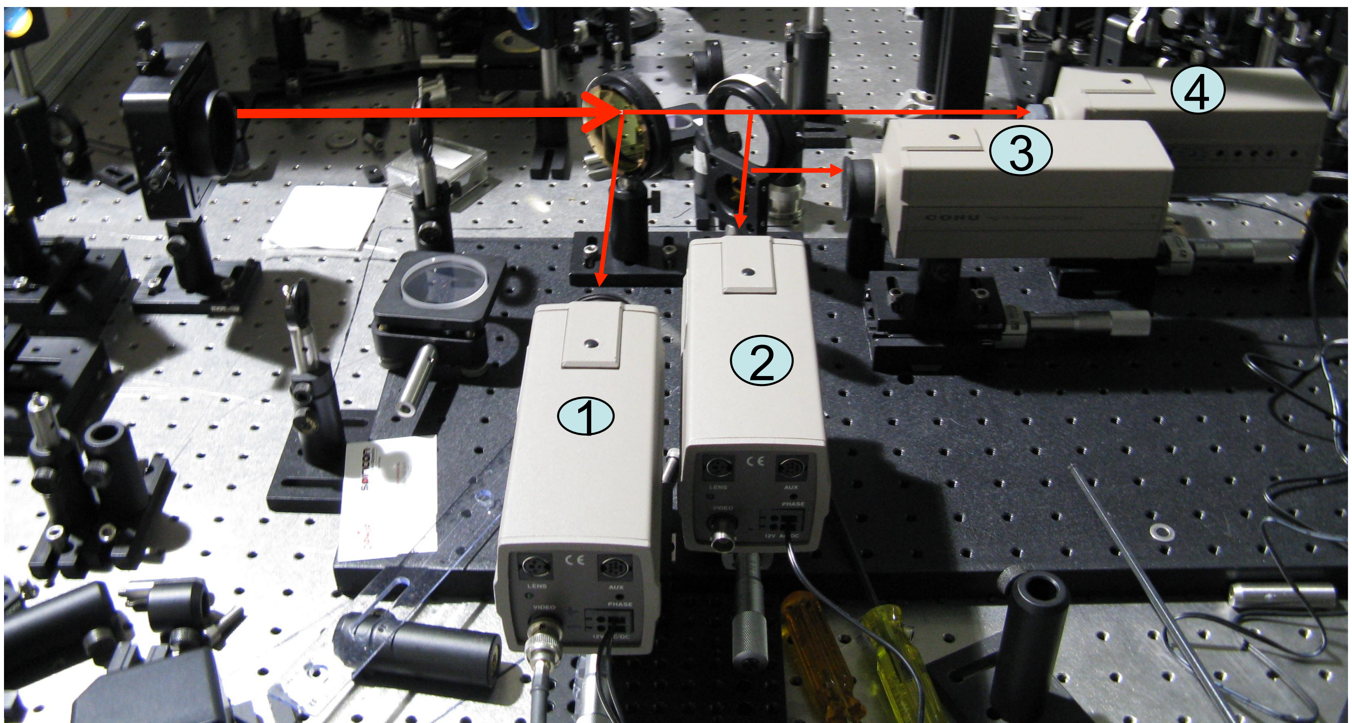
M. Labat et al, PRL 103, 264801 (2009)

X.J. Wang *et al*, PRL **103**, 154801 (2009).

Transverse Mode Evolution of a FEL Pulse

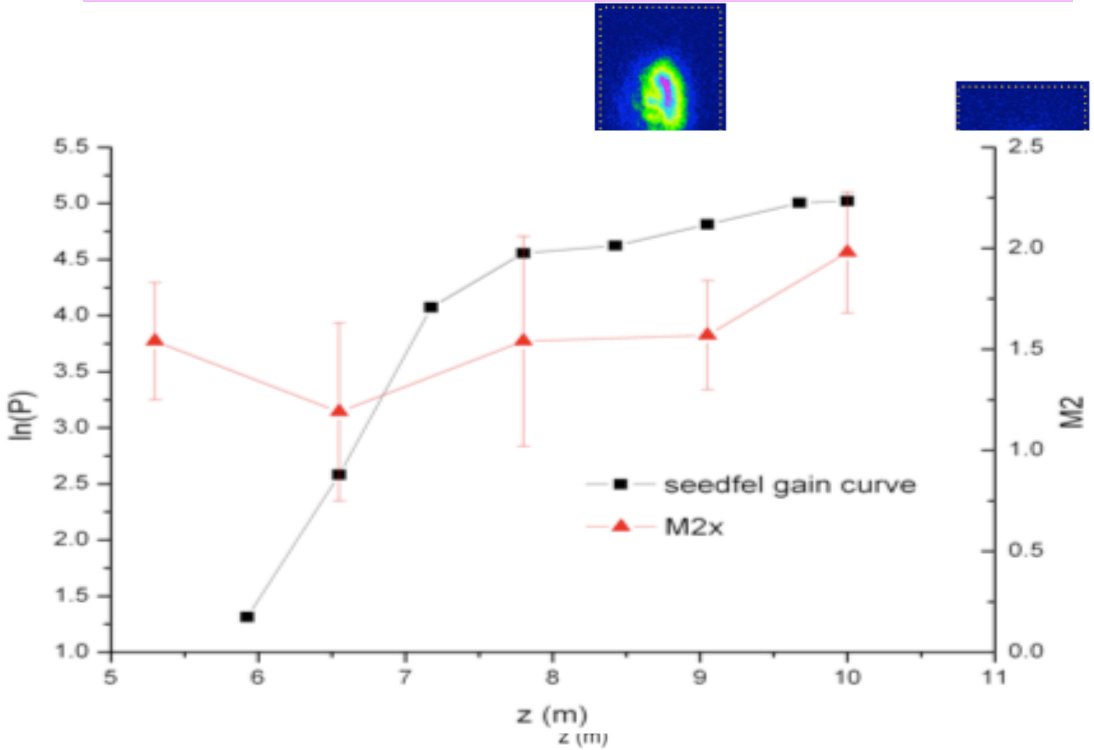
M^2 is the quantity measuring the FEL beam mode contents (quality).

e⁻ beam	$\sigma_x(z)^2 = \varepsilon_x(\beta_x^0 + \frac{1}{\beta_x^0}(z-z_0)^2)$	σ_x	ε_x	β_x^0
		$\sim$	$\sim$	$\sim$
laser	$\sigma_r(z)^2 = M^2\frac{\lambda}{4\pi}(Z_R + \frac{1}{Z_R}(z-z_0)^2)$	σ_r	$M^2\frac{\lambda}{4\pi}$	Z_R



Transverse Mode Evolution of a FEL Pulse

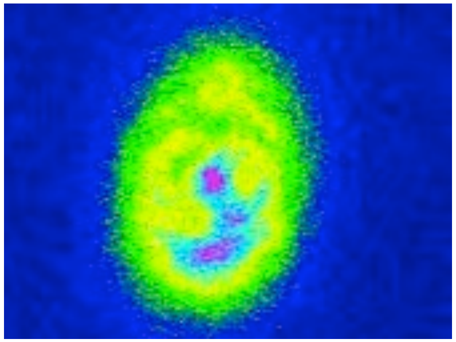
Saturation Regime

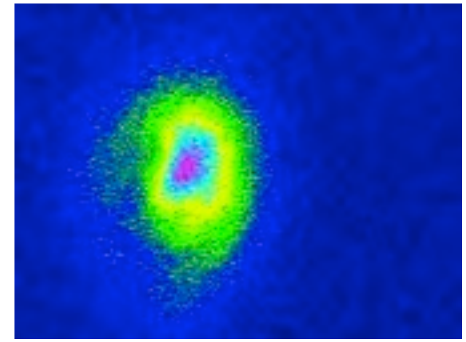


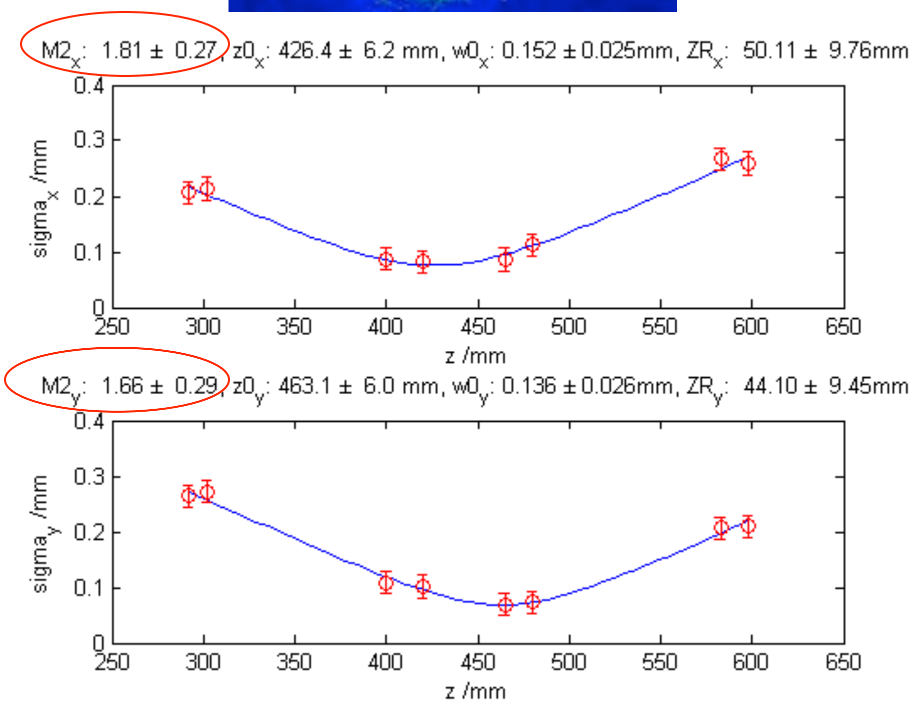
SASE FEL

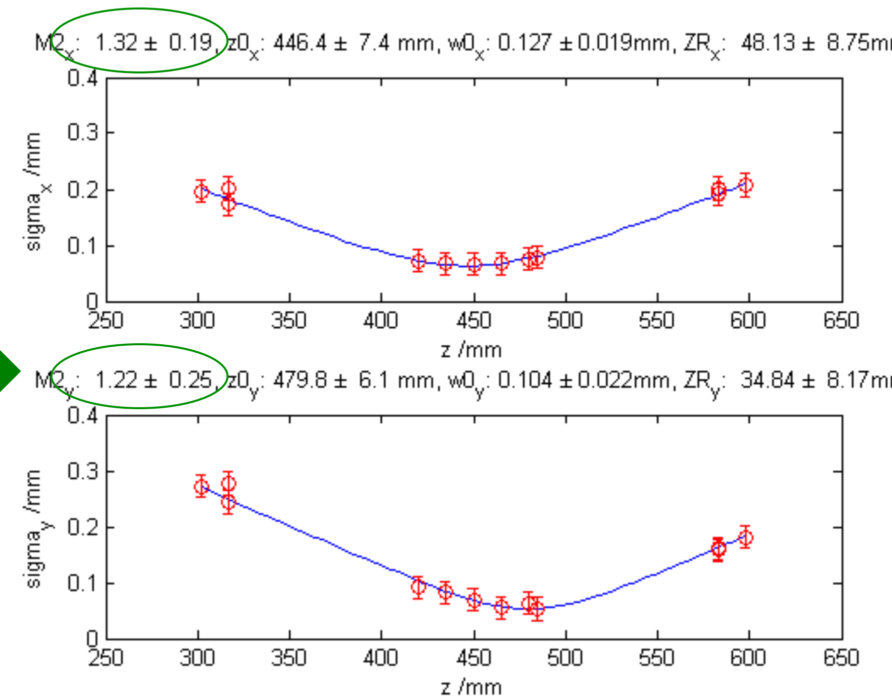
Laser Seeded FEL

Transverse Beam Quality Improvement





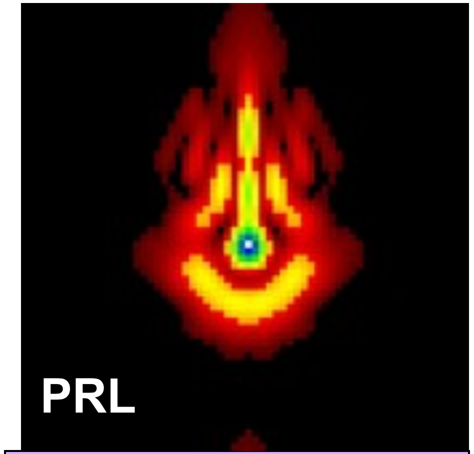




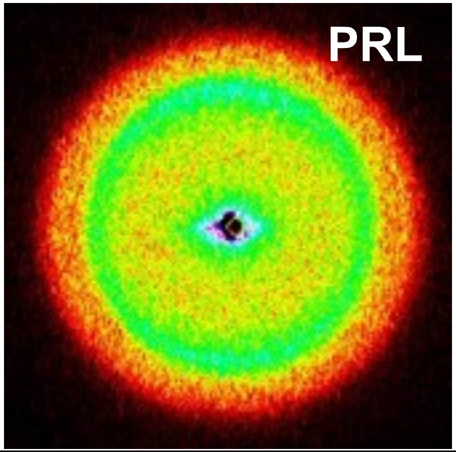
Uniform Undulator

Tapered Undulator

Conclusion Remark



80fs Superradiance



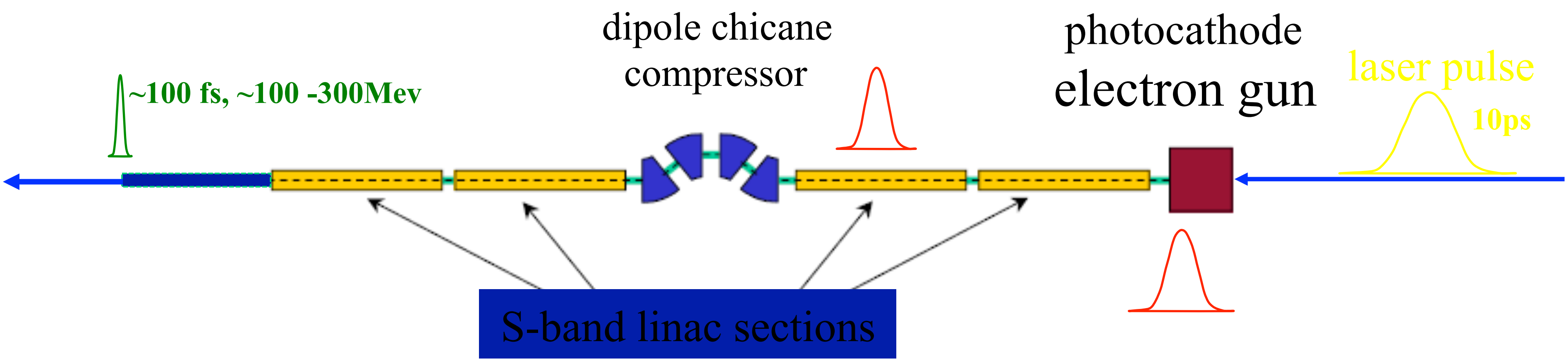
XUV Photochemistry

Tapering is the key technology to improve and preserve the FEL performance beyond the saturation (both SASE and seeded FELs).

Great progress made in seeded FEL amplifiers, more exciting results expected in next few years:

- HHG seeding in soft X-ray.
- Experimental demonstration of new schemes – self seeding, EEHG, HEHG...
- Hard X-ray Oscillator FEL.

Ultra-Short Electron Pulse Generation @SDL

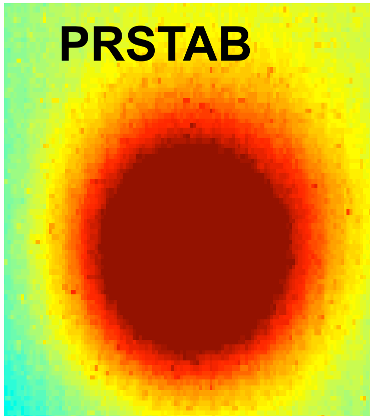


We report the measurement of very short, high-brightness bunches of electrons produced in a photocathode rf gu[...] the bunch were measured by passing the energy chirped the electron beam through a momentum selection slit while varying the phase of the rf linac. The bunch compression as a function of rf gun phase and electric field at the cathode were investigated. The shortest measured bunch is 370±100 fs (at 95% of the charge) with 2.5×10^8 electrons (170 A peak current); the normalized rms emittance of this beam was measured to be 0.5π mm mrad and the energy spread is 0.15%. [S1063-651X(96)51110-4]

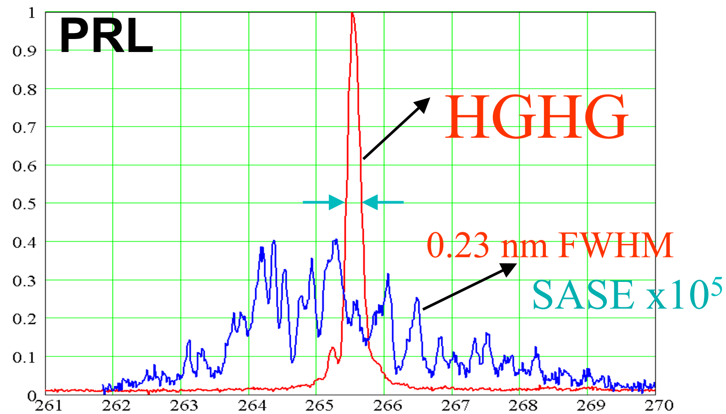
P. Piot et al, Phys. Rev. STAccel. Beams **6, 033503 (2003).**

X.J. Wang et al, Phys. Rev. **E** , **54**, No.4, R3121 -3124 (1996).

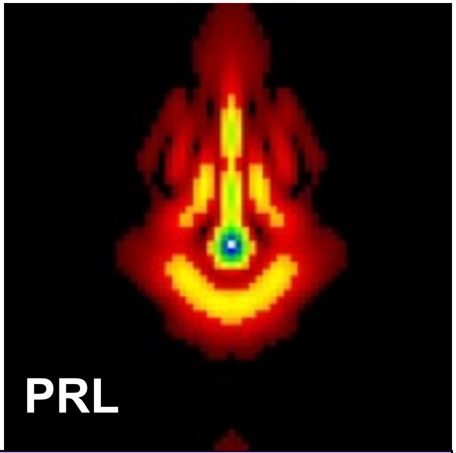
Cutting Edge Accelerator Science at the SDL



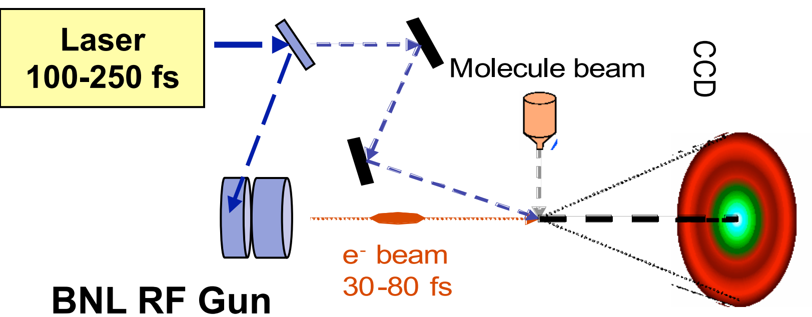
SASE @ 210 nm



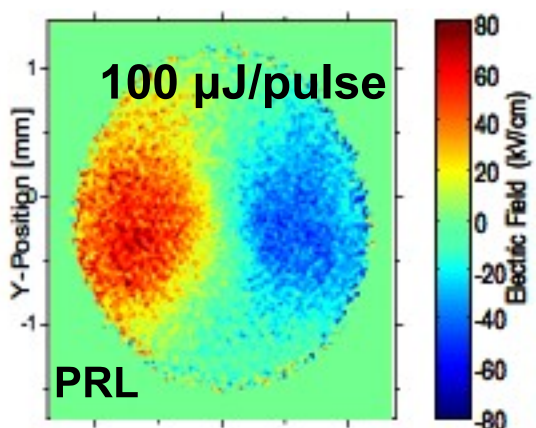
HGHG FEL @ 266 nm



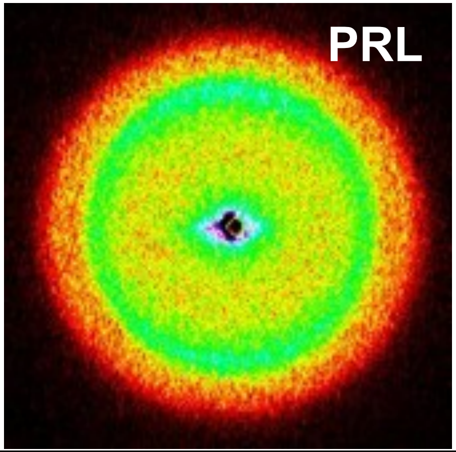
80fs Superradiance



Ultrafast Electron Diffraction



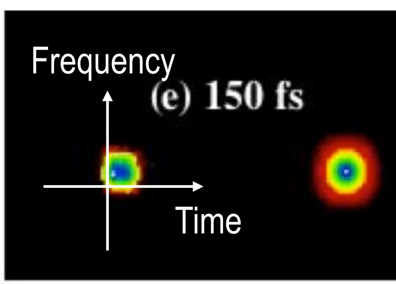
High Intensity THz

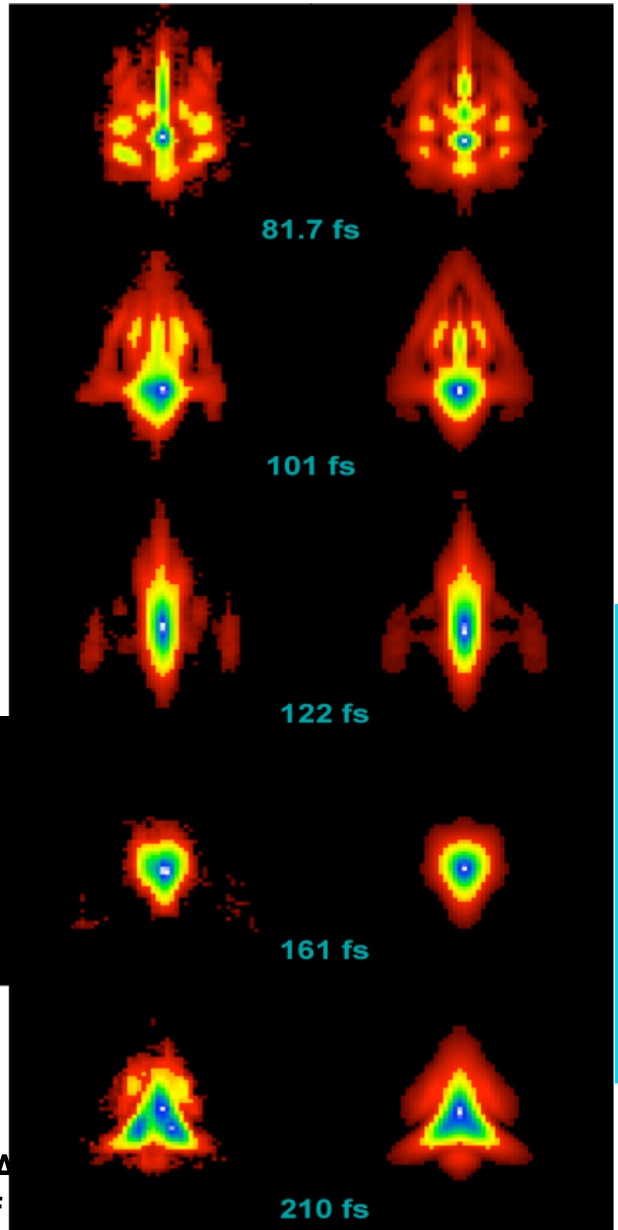


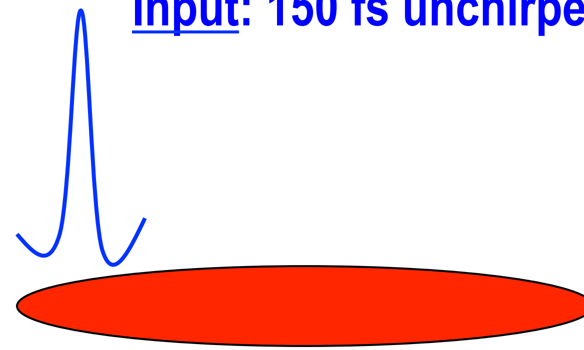
XUV Photochemistry

Superradiance in a Short Pulse FEL Amplifier Beyond Saturation

FROG Traces







<u>**Output**</u>

- **<u>Exp Gain Regime</u>: BW shrinks as $z^{-1/2}$ & pulse length grows**
- **<u>SupRad</u>: Pulse length shrinks beyond saturation to ~ 80 fs**

T. Watanabe et al, PRL **98**, 034802 (2007).