An Adventure in Marrying Laser Arts and Accelerator Technologies

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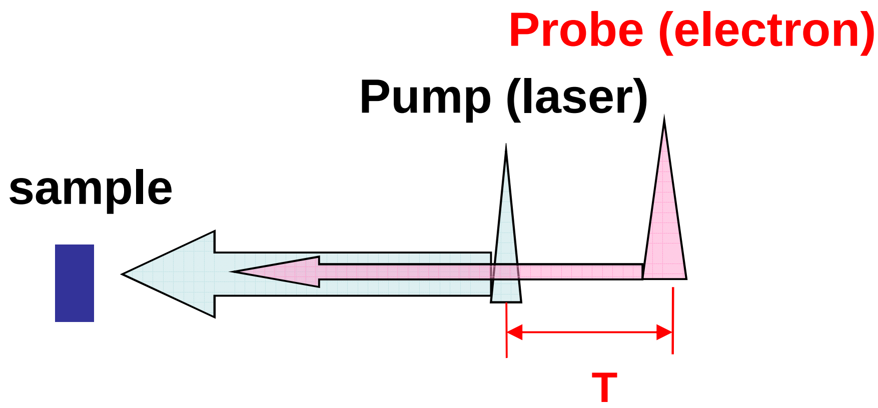
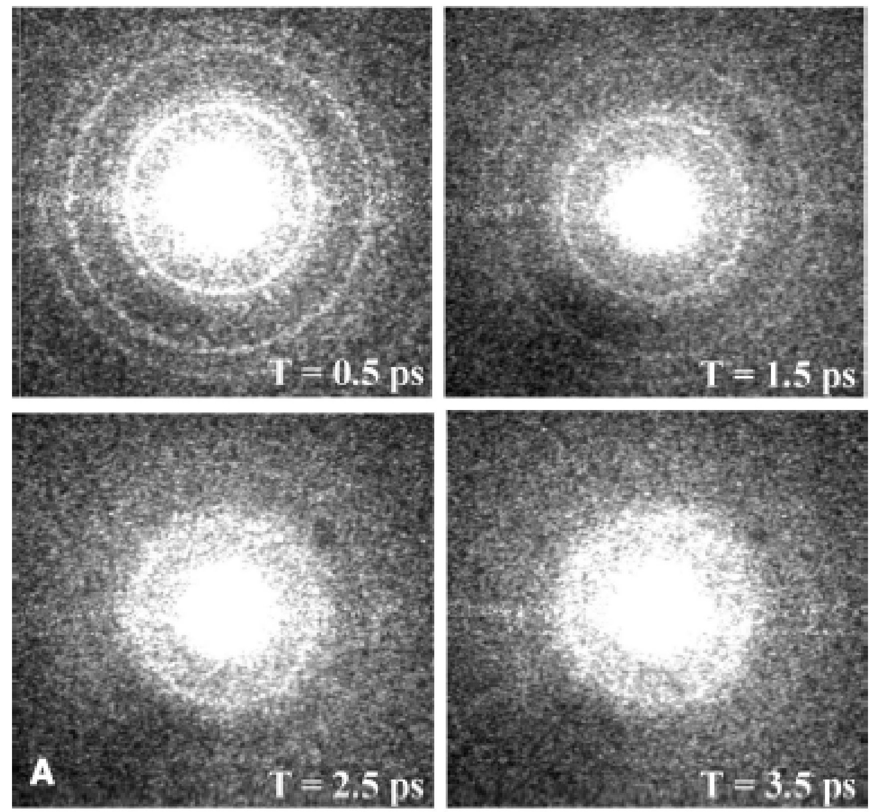
Feb-28-2012

An example



Typical pump-probe experiment

- **Light source frontiers:**
  - **Shorter pulse width**
  - **More photons**
  - **Narrower bandwidth**
  - **Lower cost**



An atomic view of phase transition in Al

Siwick et al, Science, 302, 1382 (2003)

Stanford, 1878

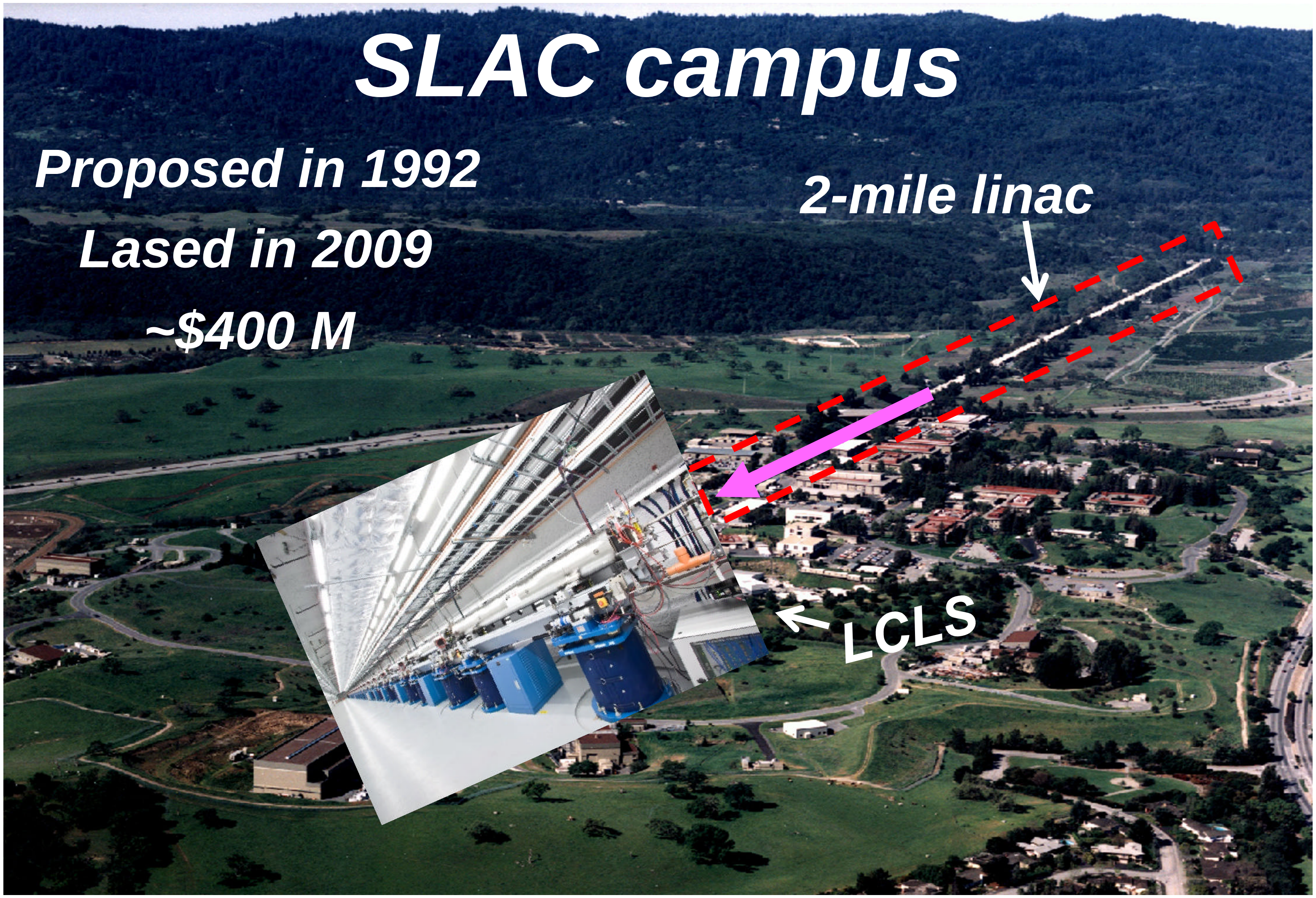
- Understanding a fast process by freezing the action

E. Muybridge

L. Stanford

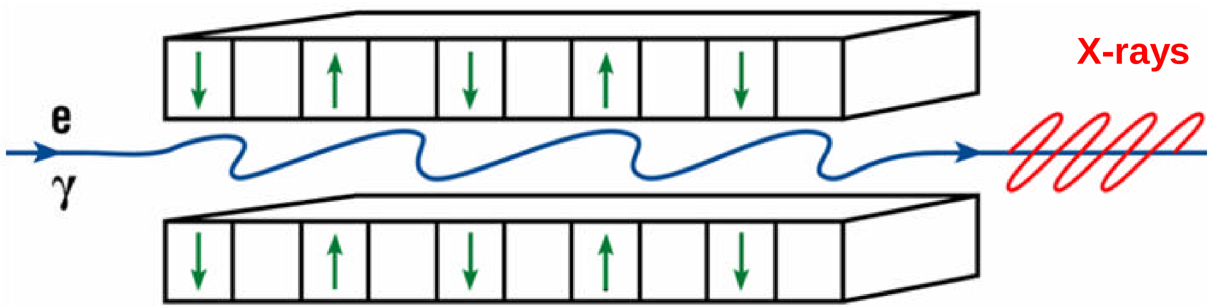
All four of a horse's feet leave the ground during a gallop?

Linac Coherent Light Source (LCLS)



Free-Electron Laser (FEL)

- **SASE (Self-Amplified Spontaneous Emission) FEL**



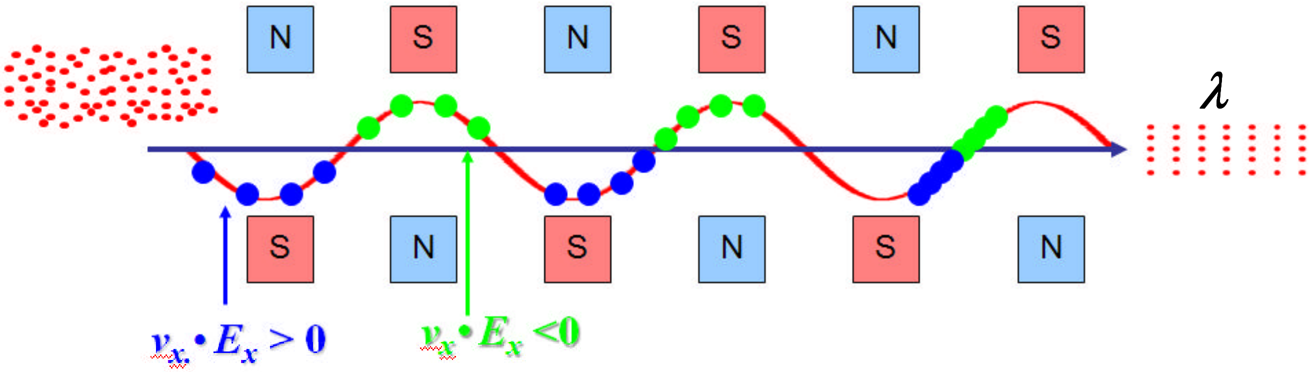
- **Send a relativistic electron beam through a long undulator**
- **Output radiation wavelength is determined by:**

$$\lambda = \frac{\lambda_w (1 + K^2/2)}{2\gamma^2} \qquad K = 0.934 B(\mathrm{T}) \lambda_w (\mathrm{cm}) \qquad \gamma = E / E_0$$

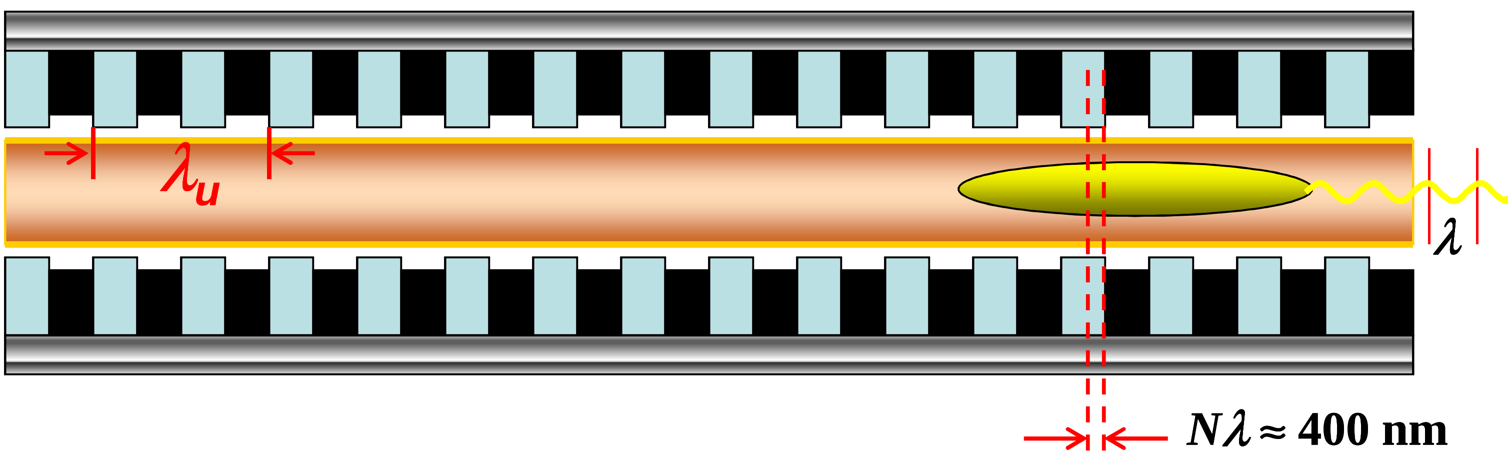
- **Wavelength can be changed by varying beam energy**
- **High energy beam (~GeV) allows generation of x-rays**
- **Radiation generated in vacuum -> no upper power limit**

Physics of a SASE FEL

- e-beam slips back w.r.t radiation by λ per undulator period
- Resonance -> sustained interaction -> bunching -> growth in power



- Coherence length << e-beam duration



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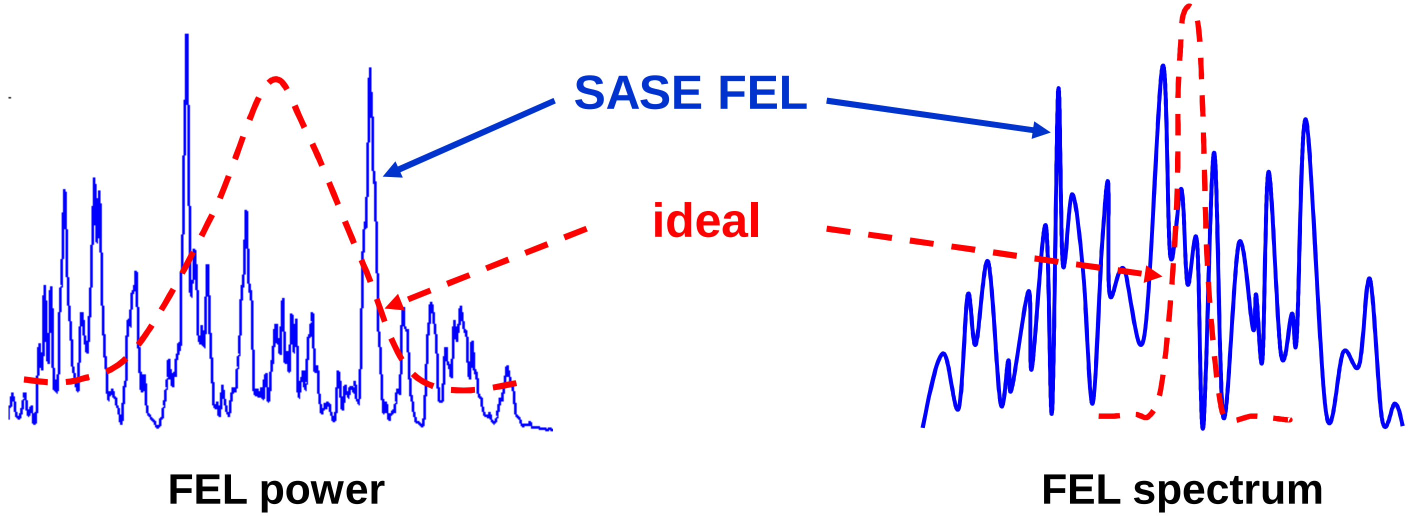
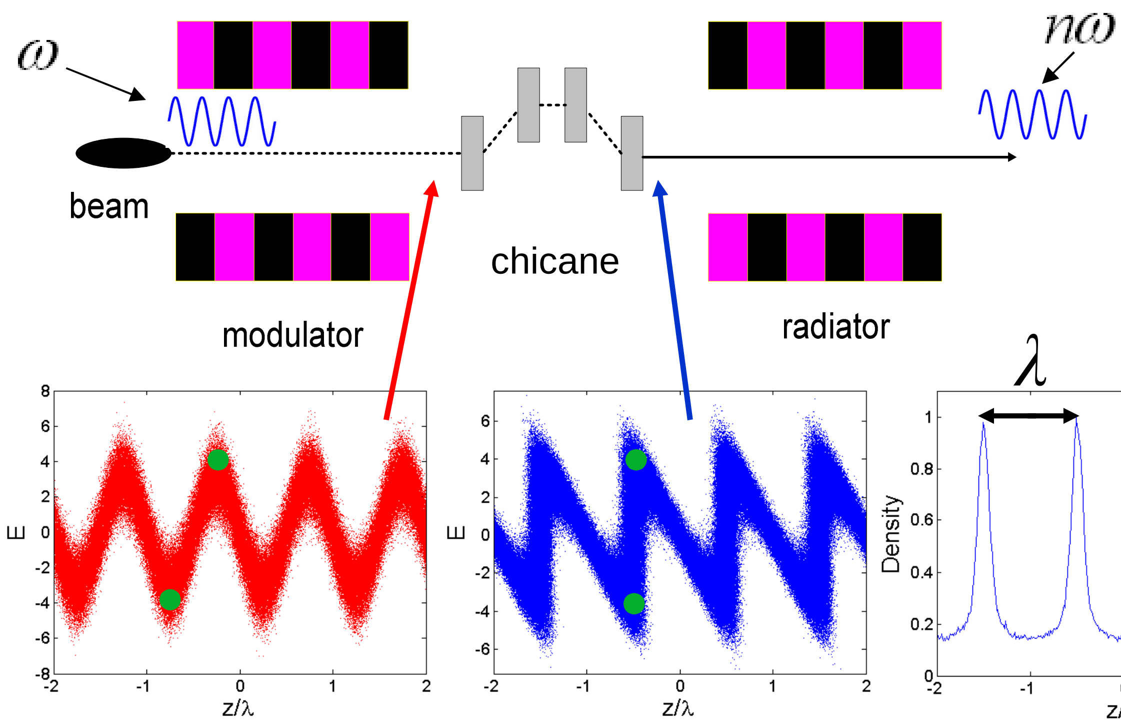
Improving the temporal coherence



- Seeding FELs to obtain fully coherent x-rays
    - Self-seeding (undulator + monochromator + undulator)
    - Seeding with high-order harmonic generation (HHG) source
    - Seeding with UV lasers + frequency upconversion

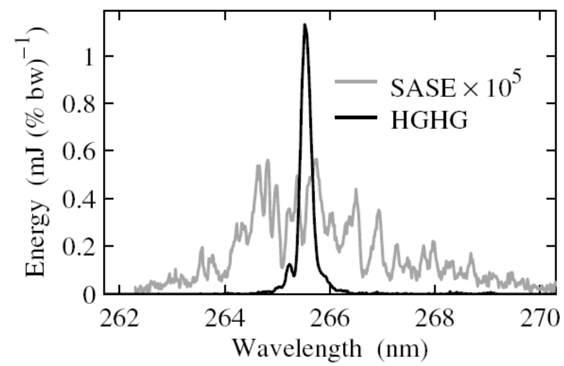
Fully coherent x-rays + well-defined timing

High-Gain Harmonic Generation (HGHG)



- Energy modulation in a modulator
- Energy modulation converted to density modulation with a chicane
- Coherent radiation at $n\omega$ amplified to saturation in a radiator

L.-H. Yu et al., Science, 2000
L.-H. Yu et al., PRL, 2003



Seed: 800 nm ➡ FEL: 266 nm

- ❑ Low up-conversion efficiency ($n \approx \Delta E / \sigma_E < 6$)
- ❑ Multiple stages to reach soft x-rays from UV seed laser

240 nm -> 60 nm
60 nm -> 15 nm
15 nm -> 5 nm

Marrying lasers and electron beams
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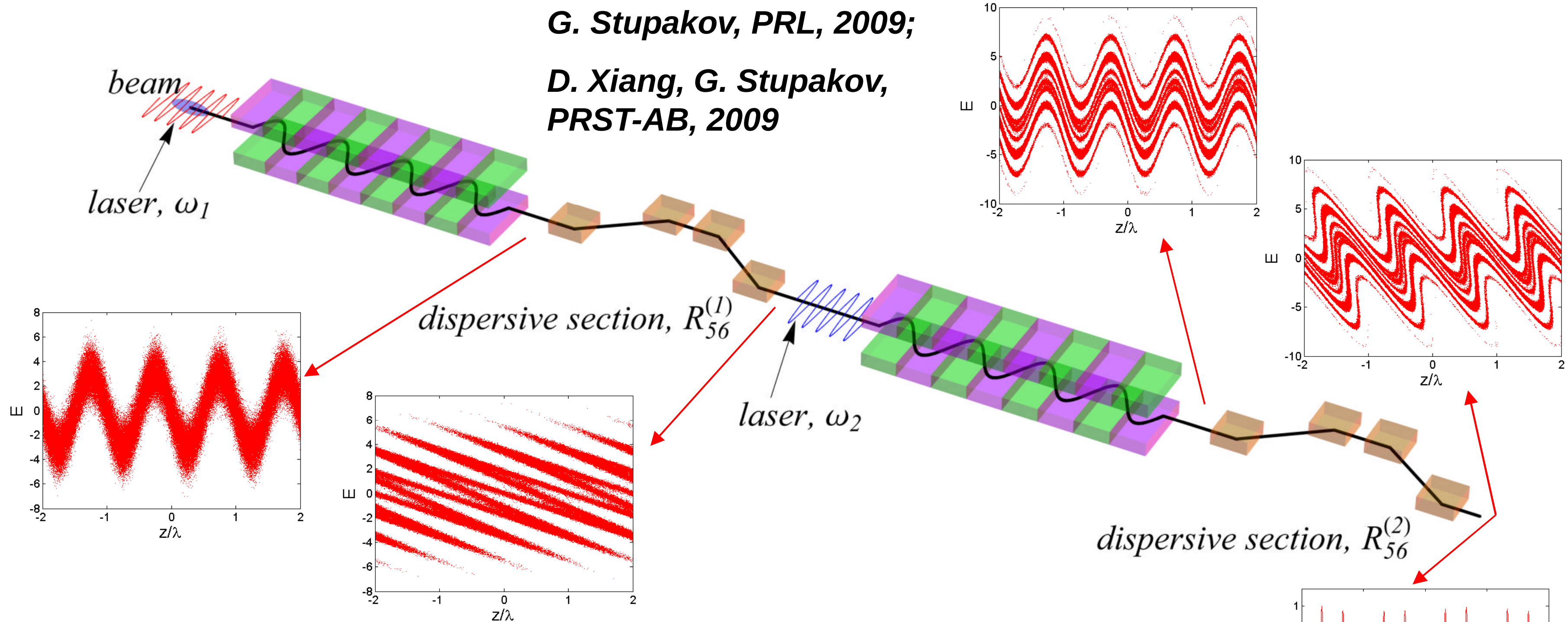
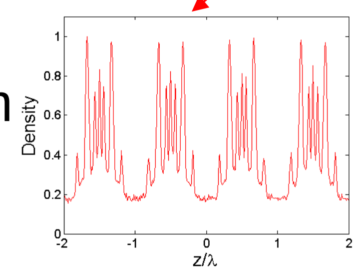
Echo-Enabled Harmonic Generation (EEHG)

G. Stupakov, PRL, 2009;

D. Xiang, G. Stupakov, PRST-AB, 2009





- First laser to generate energy modulation in electron beam
- First strong chicane to split the phase space
- Second laser to imprint energy modulation
- Second chicane to convert energy modulation into density modulation

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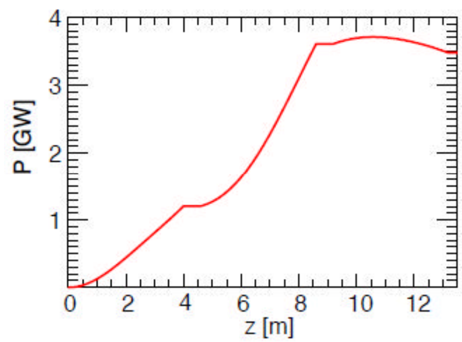
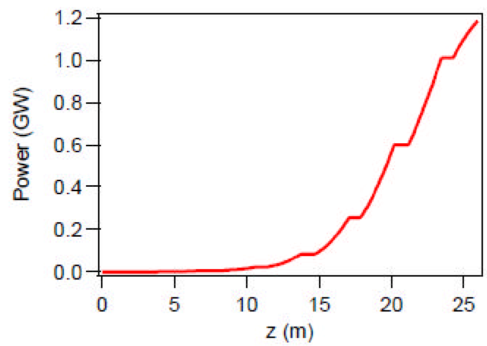
Echo FEL: Promises and Challenges

- **Promises**
  - **Remarkable up-frequency conversion efficiency: $b_n \sim n^{-1/3}$**
  - **UV laser -> soft x-rays in a single stage**
  - **World-wide interest: China / France / Italy / Switzerland / UK / USA**



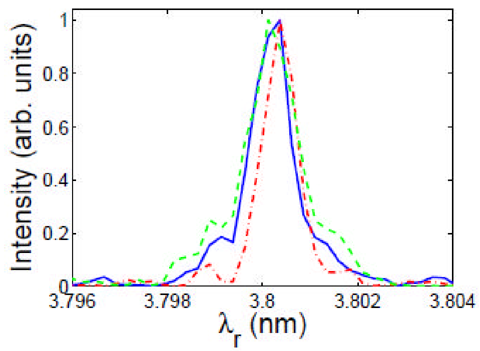
SwissFEL

Switzerland



FERMI FEL

Italy



NGLS

LBNL, USA

- **Challenges**
  - **Preservation of long-term (~ns) memory of phase space correlations**
  - **CSR in chicanes; quantum diffusion; introbeam scattering, etc**

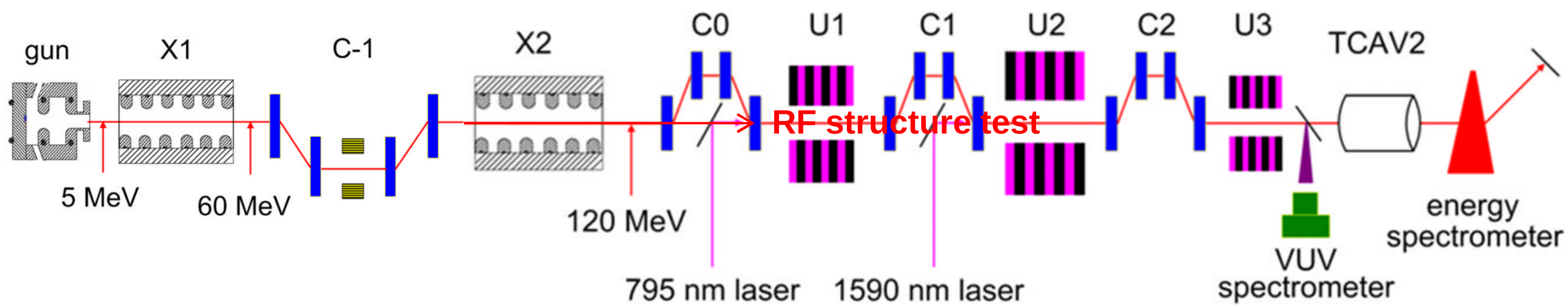
Preserve long-term memory

Courtesy of Youtube

- Laminar flow: a fluid flows in parallel layers with no disruption between the layers

- Very similarly, under conservative forces beam phase spaces do not mix

Next Linear Collider Test Accelerator (NLCTA)

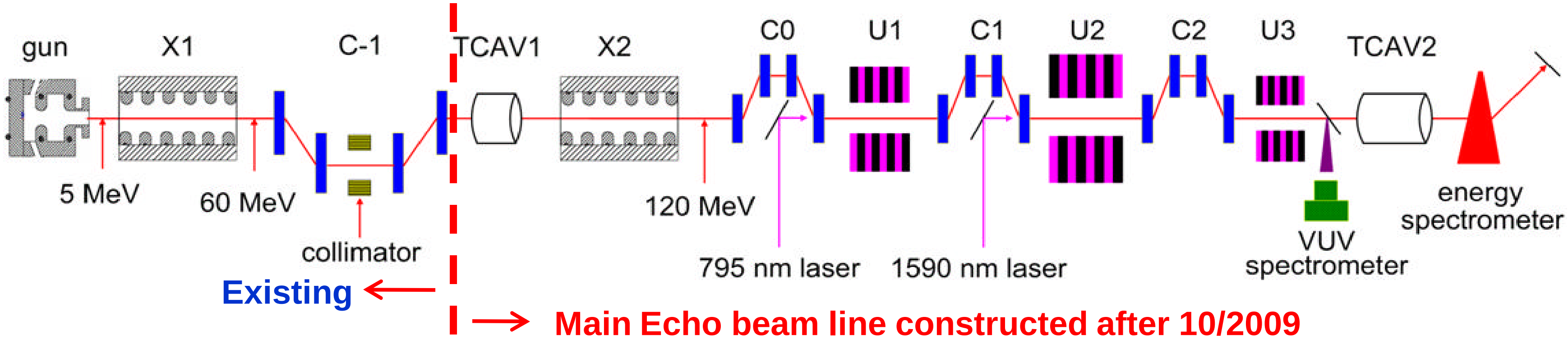


- **Old NLCTA mainly for laser acceleration and rf structure test**
- **Reconfigured for testing ECHO scheme**
  - An additional x-band rf structure to boost beam energy to 120 MeV
  - 3 chicanes and 3 undulators
  - Laser system and laser transport
  - Quadrupoles, correctors, power supplies
  - OTR, YAG screens, VUV spectrometer, DAQ

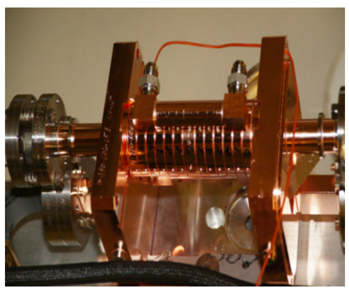
Road to Echo-7

- 03-2009: First planning meeting
- 06-2009: Conceptual design finished (funded with $800 k)
- 09-2009: BES funding arrived
- 12-2009: 120 MeV beam achieved
- 03-2010: Beam line completed
- 04-2010: Electron-laser interaction achieved
- 05-2010: First harmonic radiation signal (EEHG+HGHG)
- 07-2010: First unambiguous echo signal (Echo- 4)
- 04-2011: Two deflecting cavities installed
- 07-2011: First Echo-7 signal obtained in realistic scenario

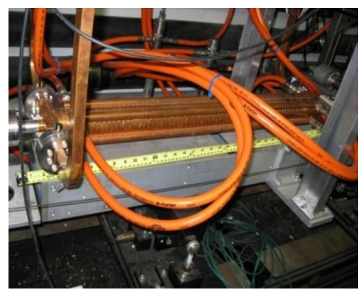
New NLCTA



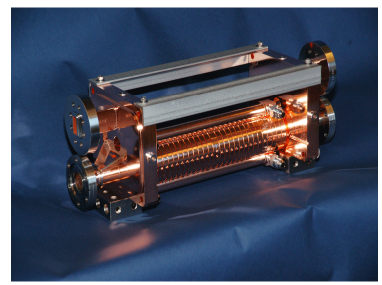
C-1



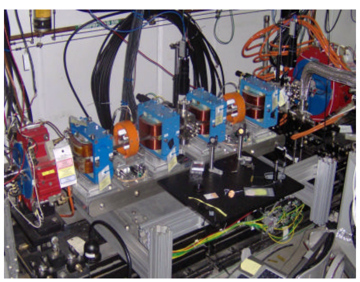
TCAV1



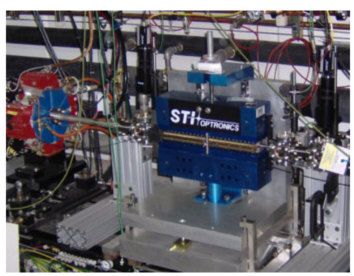
X2



TCAV2

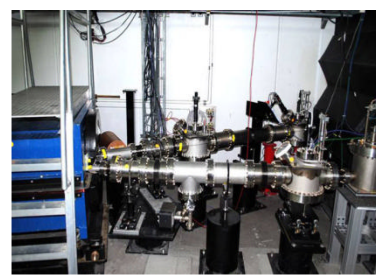


C1



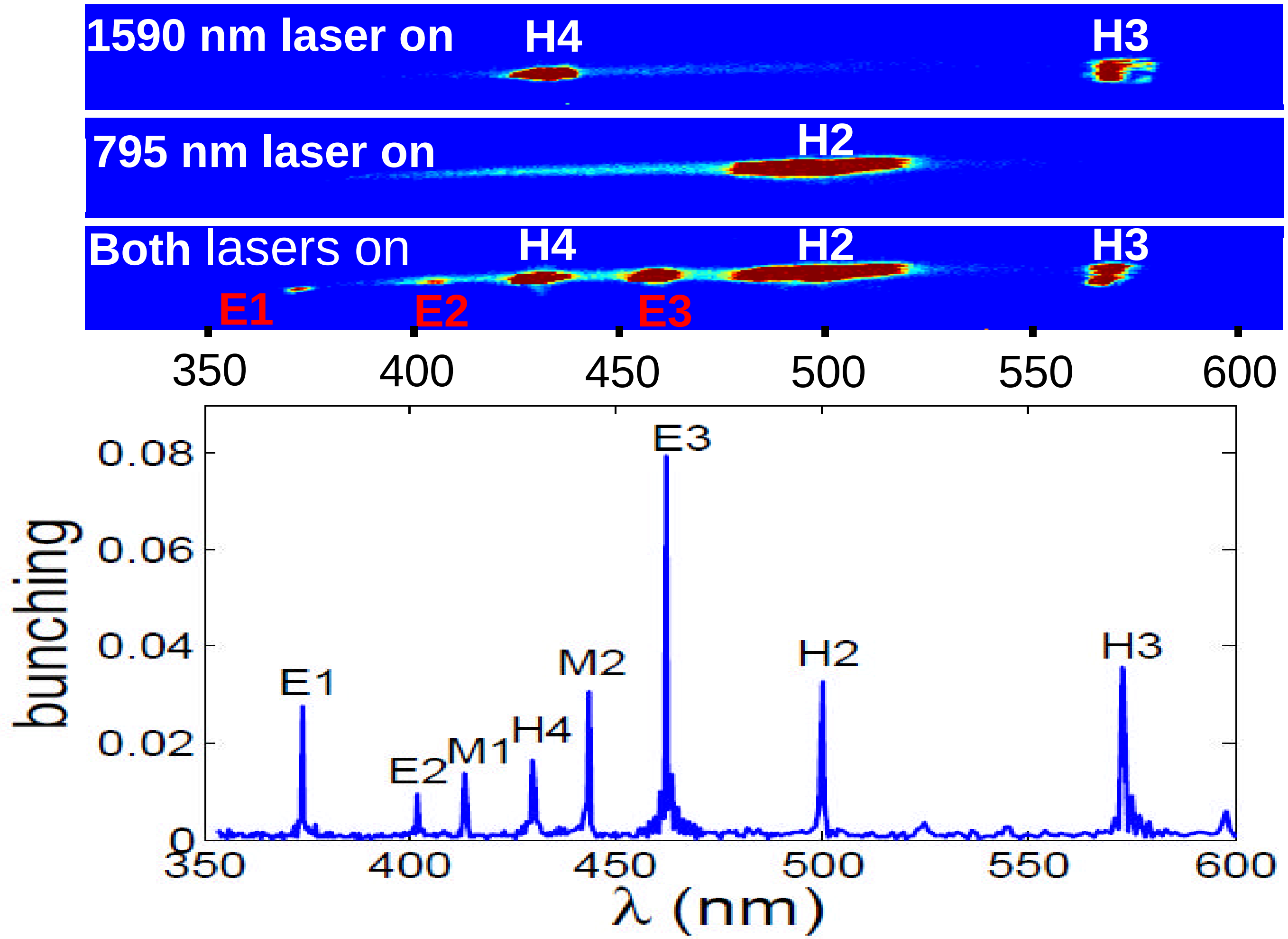
U1

U2



spectrometer

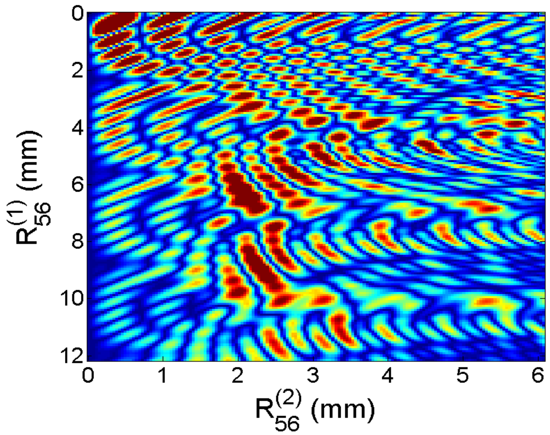
First demonstration of EEHG



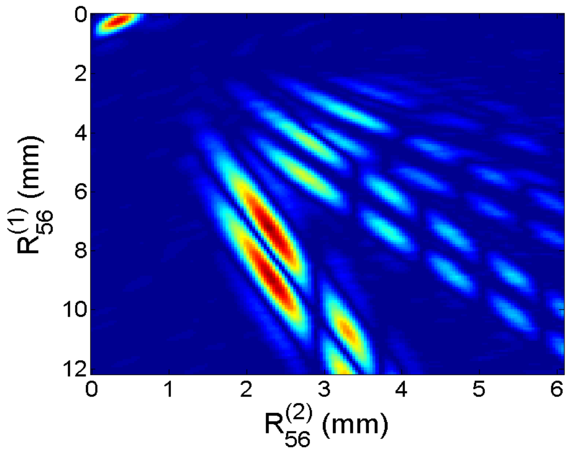
D. Xiang *et al., PRL 105, 114801* (2010)

"The theory and experimental realization of EEHG are both groundbreaking, with profound implications for FEL science."
--*Nature Photonics*, 4, 739 (2010)

EEHG in the realistic scenario

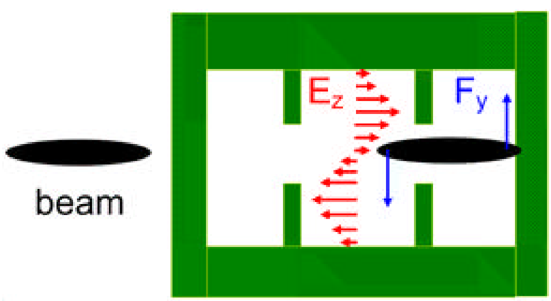


$\Delta E / \sigma_E = 80$



$\Delta E / \sigma_E = 2$

- **Transverse cavity (TCAV) 'heater' to increase slice energy spread**



$y' = y_0' + kz_0$ Measure bunch length

$\delta = \delta_0 + ky_0$ Increase slice energy spread

Behrens, Xiang and Huang, PRST-AB, 15, 022802 (2012)

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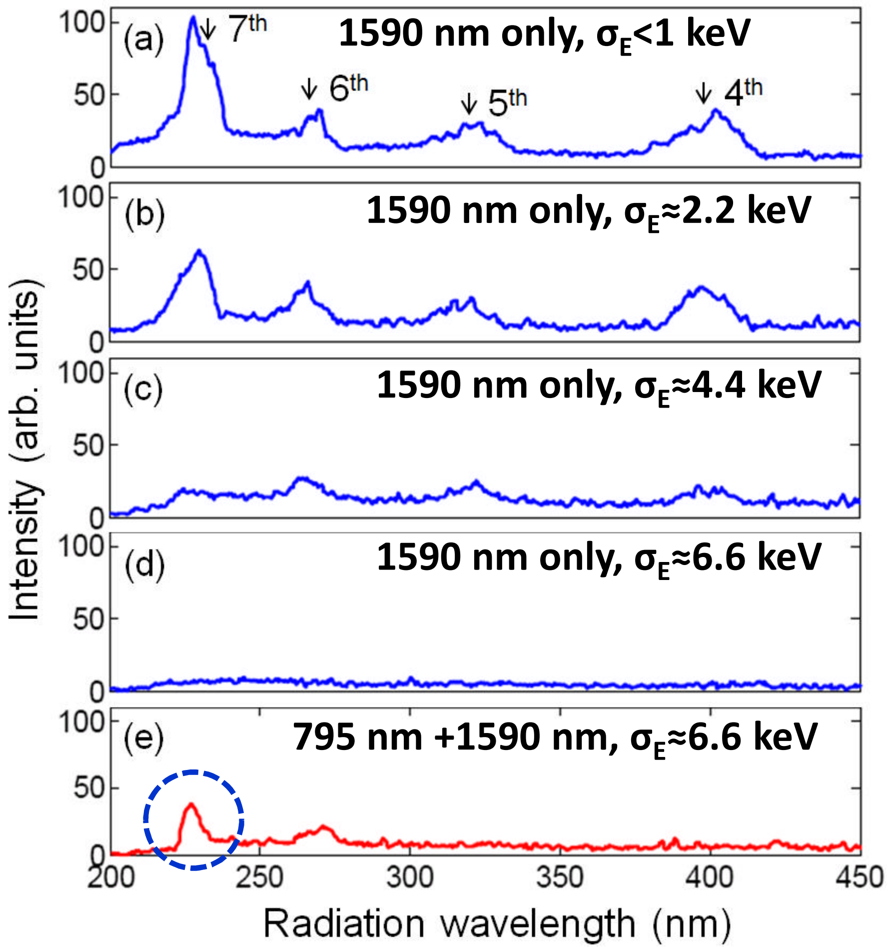
Echo-7: mission accomplished

❑ **Evidence of high harmonics from EEHG**



- **Two TCAVs and a VUV spectrometer installed in 04/2011**
- **4th to 7th harmonics from HGHG suppressed with increased beam slice energy spread**
- **7th harmonic from EEHG generated when energy modulation is about 2~3 times the beam slice energy spread**

D. Xiang et al., PRL, 108, 024802 (2012)

Other applications of ‘laser + beam’

A few examples

- Narrow-band THz emission from laser-modulated beam
- Isolated attosecond x-ray pulse
- Mode-locked x-rays
- Laser assisted emittance exchange
- Femtosecond x-rays in a strong ring using angular-modulated electron beam

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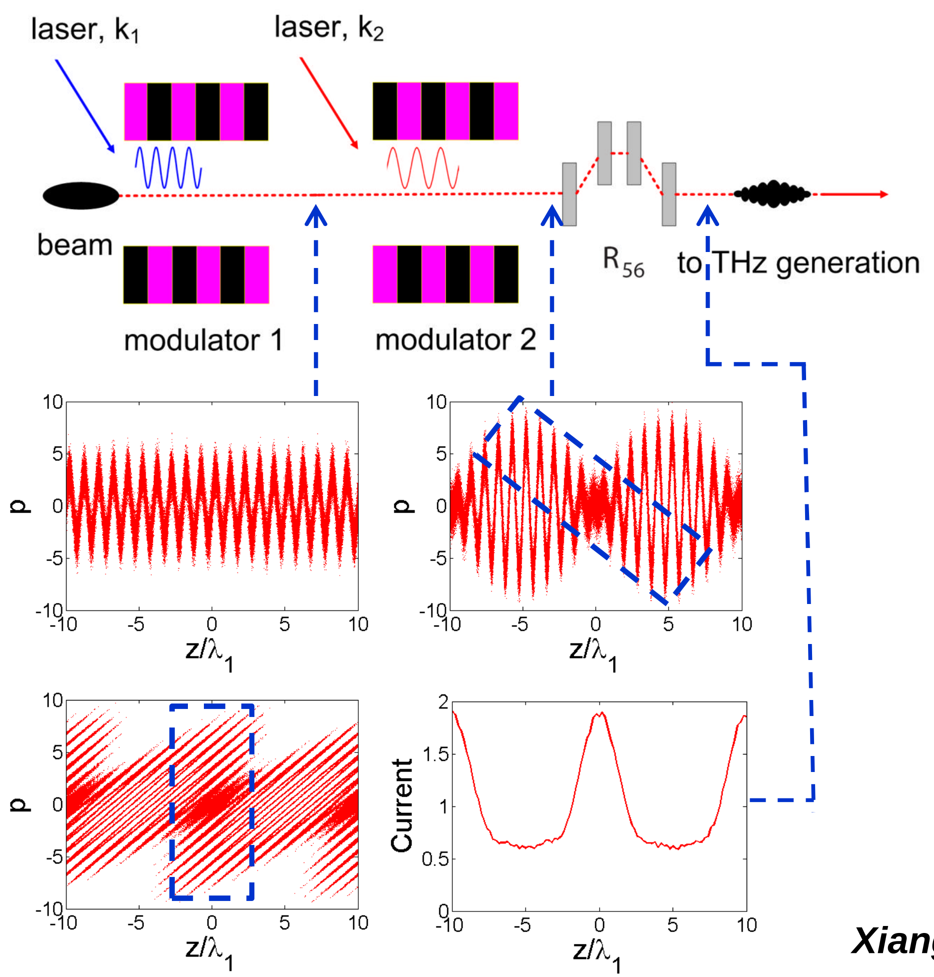
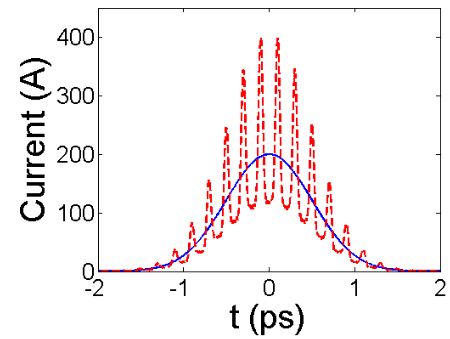
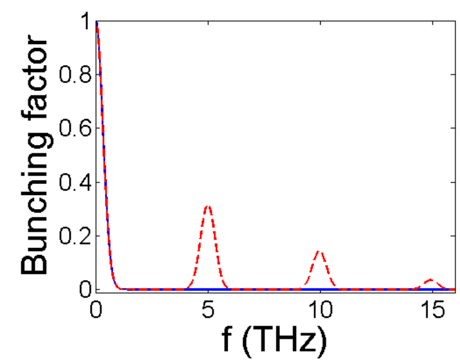
Narrow-band THz from laser-modulated beam

- Using the relativistic electron beam as the nonlinear medium





Beam current



Radiation spectrum

Xiang and Stupakov, PRST-AB, 12, 080701 (2009)

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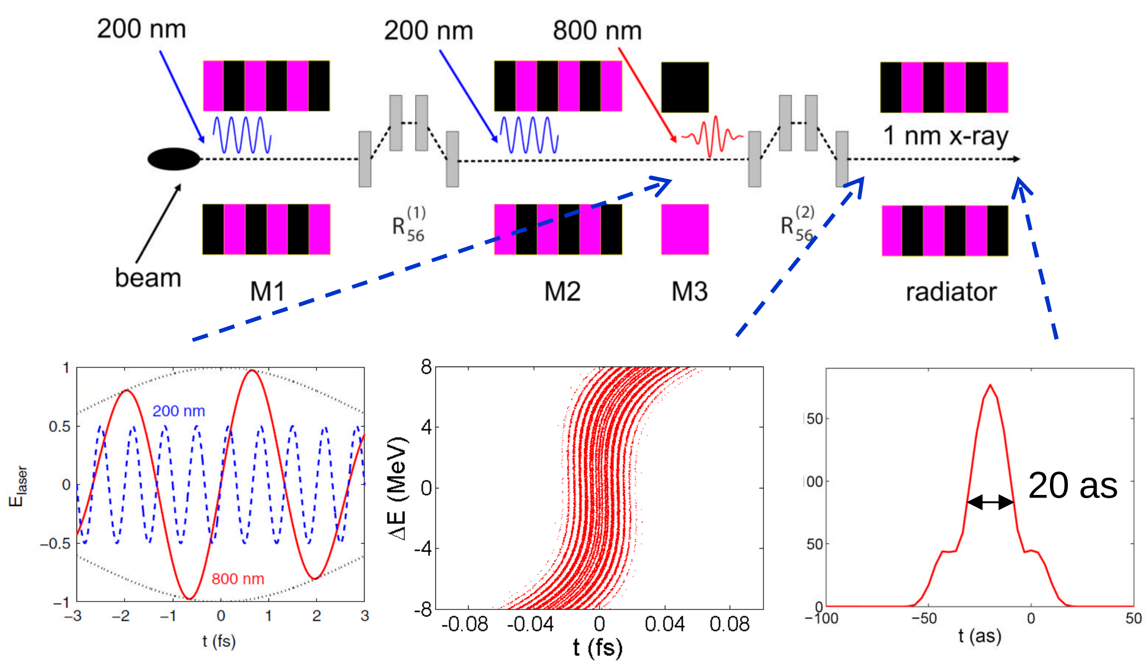
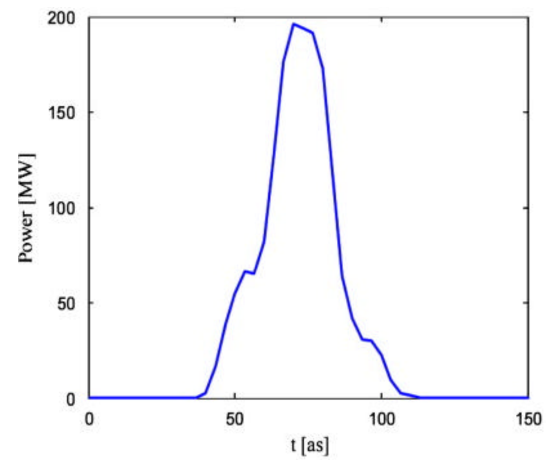
Attosecond x-ray pulse

- A few-cycle Infrared (IR) laser is used to imprint an energy chirp for bunch compression, which extends the harmonic number to a few hundred
- A few-cycle Infrared (IR) laser for selection of an isolated attosecond pulse



Xiang et al., PRST-AB, 12, 060701 (2009)



FEL power profile from 3-D simulation

Yan et al., NIM A 621, 97 (2010)

Two-color attosecond x-ray pulses, Zholents and Penn, NIM A, 612, 254 (2010)

Other applications of ‘laser + beam’

A few examples

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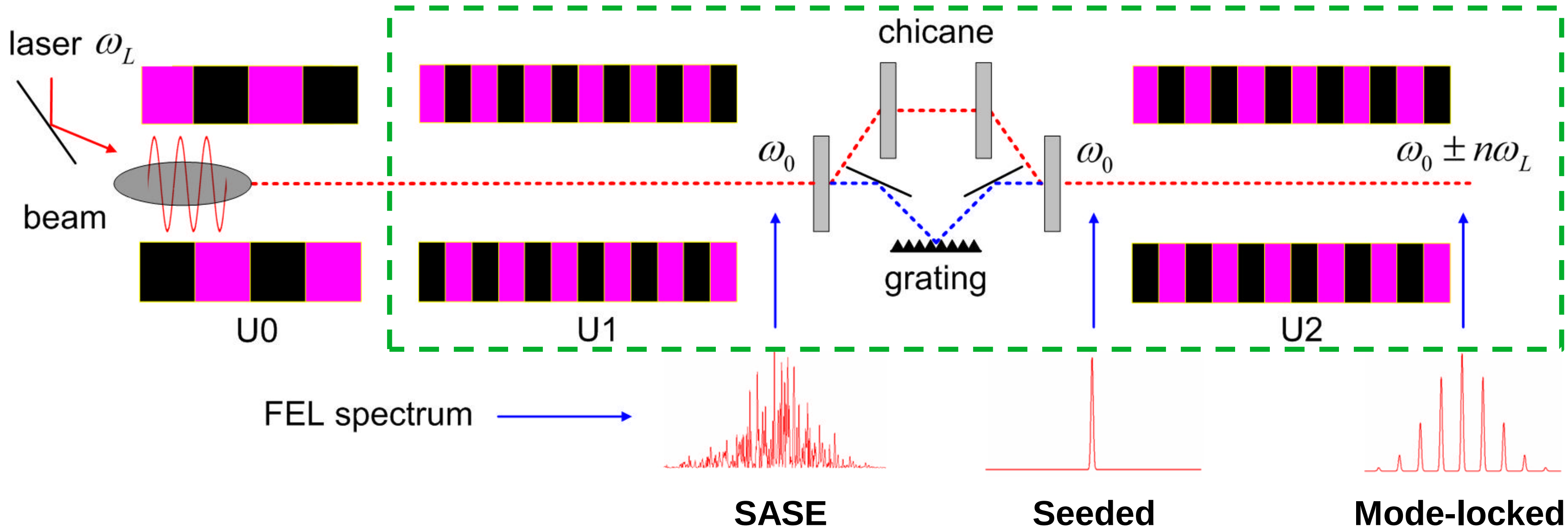
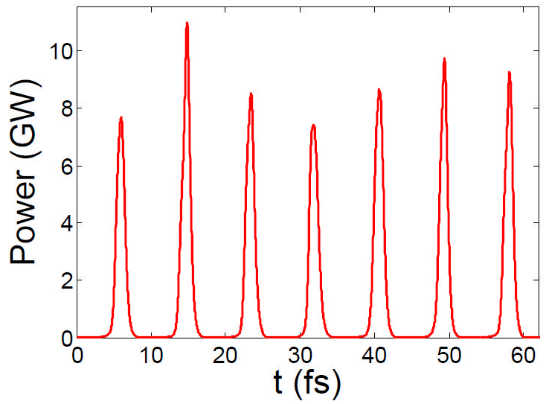
Mode-locked x-rays

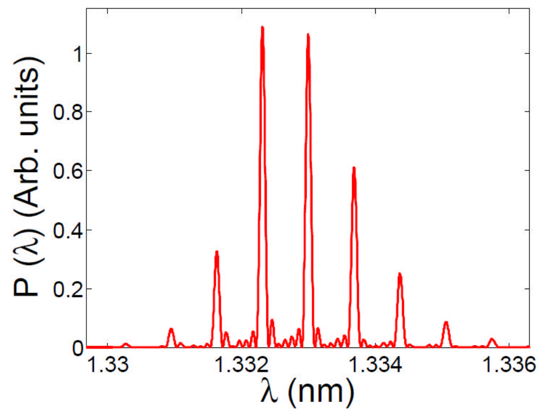


- **Explore the dynamics of a large number of atomic states simultaneously**
- **Physics of mode locking x-rays**
  - **Modulating the amplitude of the seed (carrier) to generate sidebands** $\omega_0 \pm \omega_L$
  - **Modulation of sidebands lead to new modes** $\omega_0 \pm 2\omega_L$ **; This process repeats……**
- **Characteristics of mode locking x-rays**
  - **X-rays span a wide frequency with equally spaced sharp lines**
  - **Attosecond pulse train**

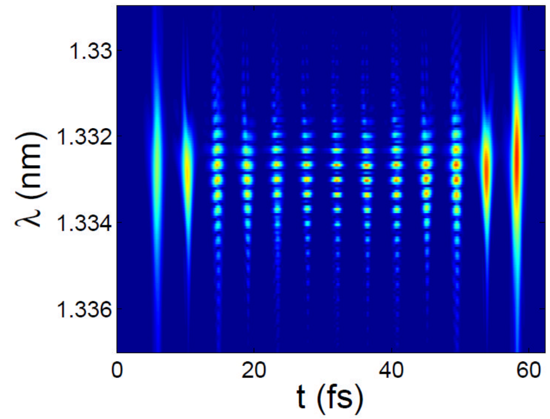
Mode-locked x-rays



FEL power



FEL spectrum



Wigner distribution

D. Xiang et al., to-be-submitted

- **~5 sharp lines equally separated by 0.5 eV**
- **~10^{11} photons per frequency line**
- **Enable single-shot x-ray spectroscopy**
- **Variable number of modes and mode spacing**
- **Naturally synchronized with modulation laser**
- **First step towards 'x-ray communications'**

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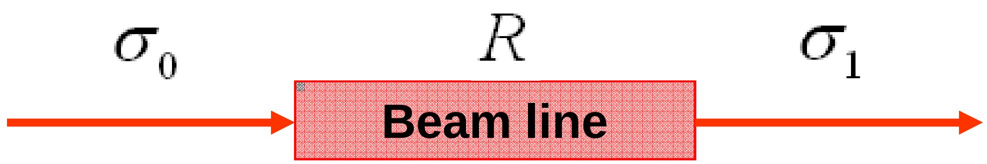
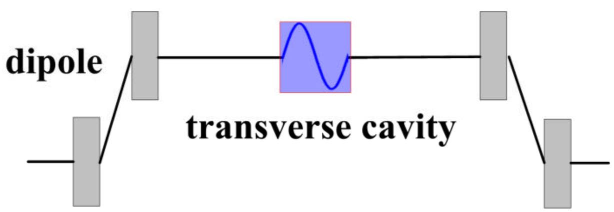
Emittance exchange (EEX)



$$\sigma_1 = R\sigma_0 R^T$$

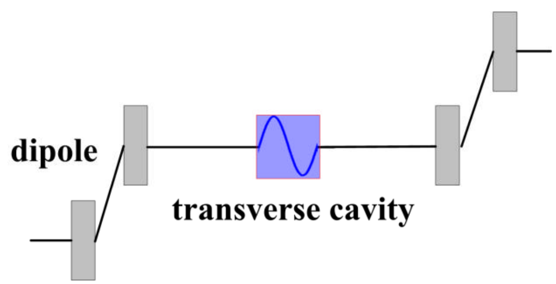
$$\begin{pmatrix} x \\ x' \\ z \\ \delta \end{pmatrix} = \begin{pmatrix} 0 & 0 & a & b \\ 0 & 0 & c & d \\ e & f & 0 & 0 \\ g & h & 0 & 0 \end{pmatrix} \begin{pmatrix} x_0 \\ x_0' \\ z_0 \\ \delta_0 \end{pmatrix}$$



Cornacchia and Emma beam line

- First EEX proposal
- Easy to implement
- EEX is not complete

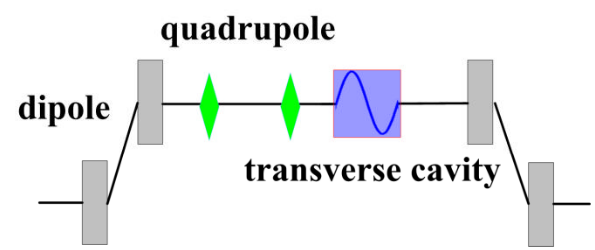
Phy. Rev. ST-AB, 5, 084001 (2002)



Kim beam line

- EEX is complete
- Dogleg introduces offsets in beam orbit

Phy. Rev. ST-AB, 9, 100702 (2006)



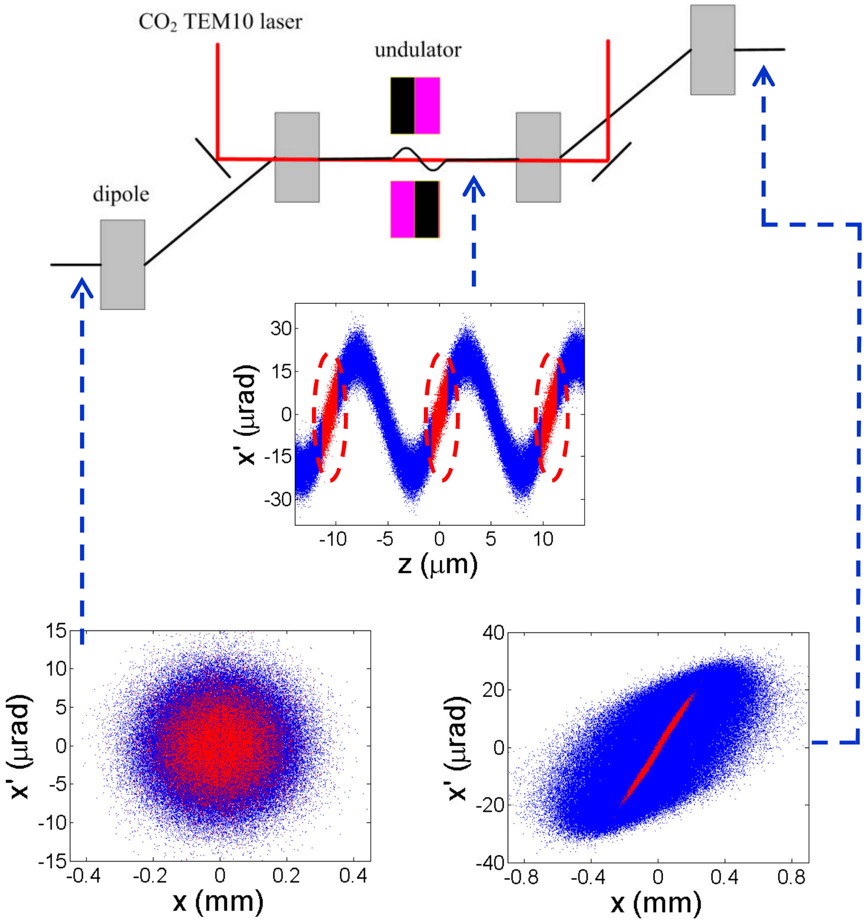
Chicane-type beam line

- -I section to reverse η
- EEX is complete
- NO offset in beam orbit

D. Xiang and A. Chao,
Phy. Rev. ST-AB, 14, 114001 (2011)

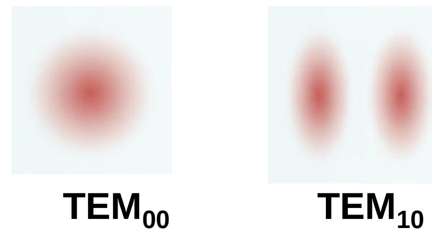
Laser assisted emittance exchange

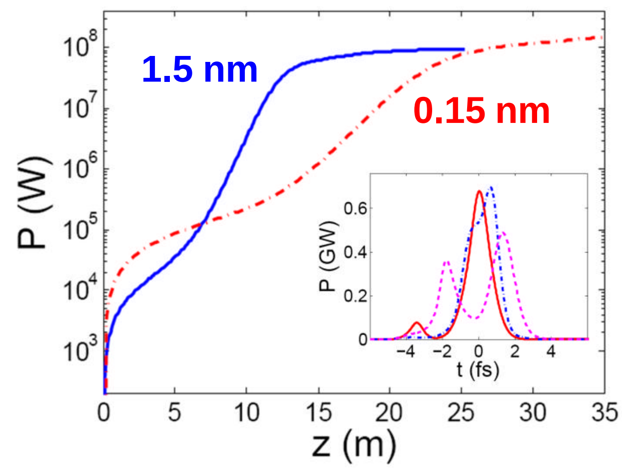
- Replacing RF transverse cavity with TEM_{10} mode laser



Before

After





Soft x-ray FEL driven by 1.2 GeV beam

Hard x-ray FEL driven by 3.8 GeV beam

D. Xiang, PRST-AB, 13, 010701 (2010)

Other applications of 'laser + beam'

A few examples

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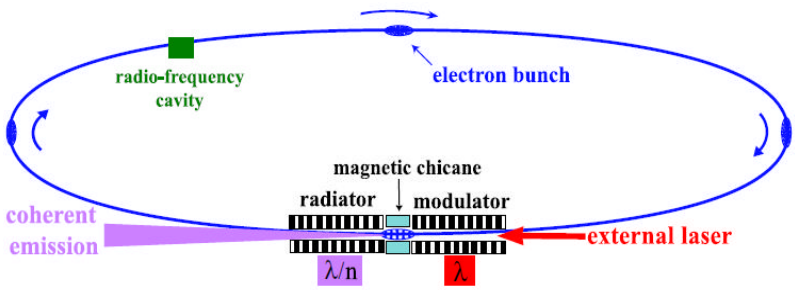
Coherent femtosecond x-rays in storage rings

Energy modulation

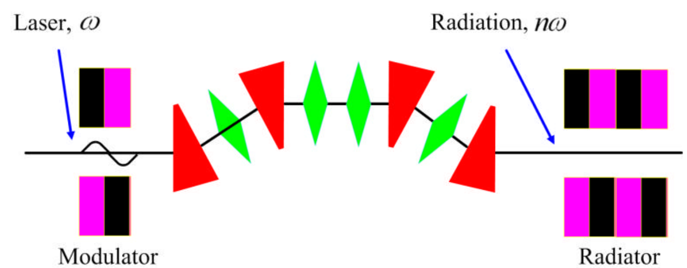


$$n \approx \frac{\Delta E}{\sigma_E}$$

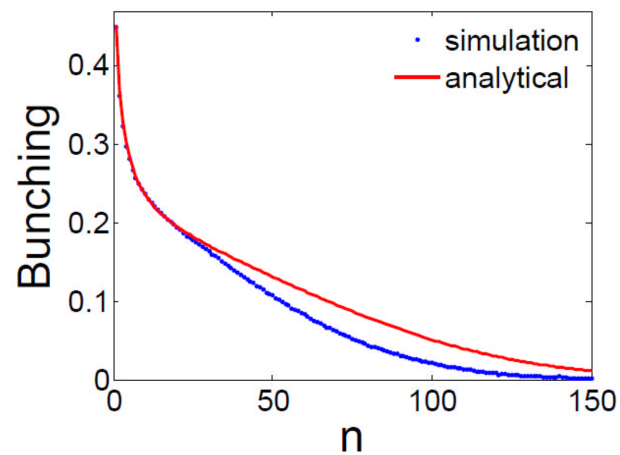
- Energy spread is large in synchrotrons (n=3 achieved so far)
- Vertical divergence is small in synchrotrons (n=100 possible)
- Using R_{54} instead of R_{56} to bunch the beam

De Ninno et al., PRL, 101, 053902 (2008)

Angular modulation

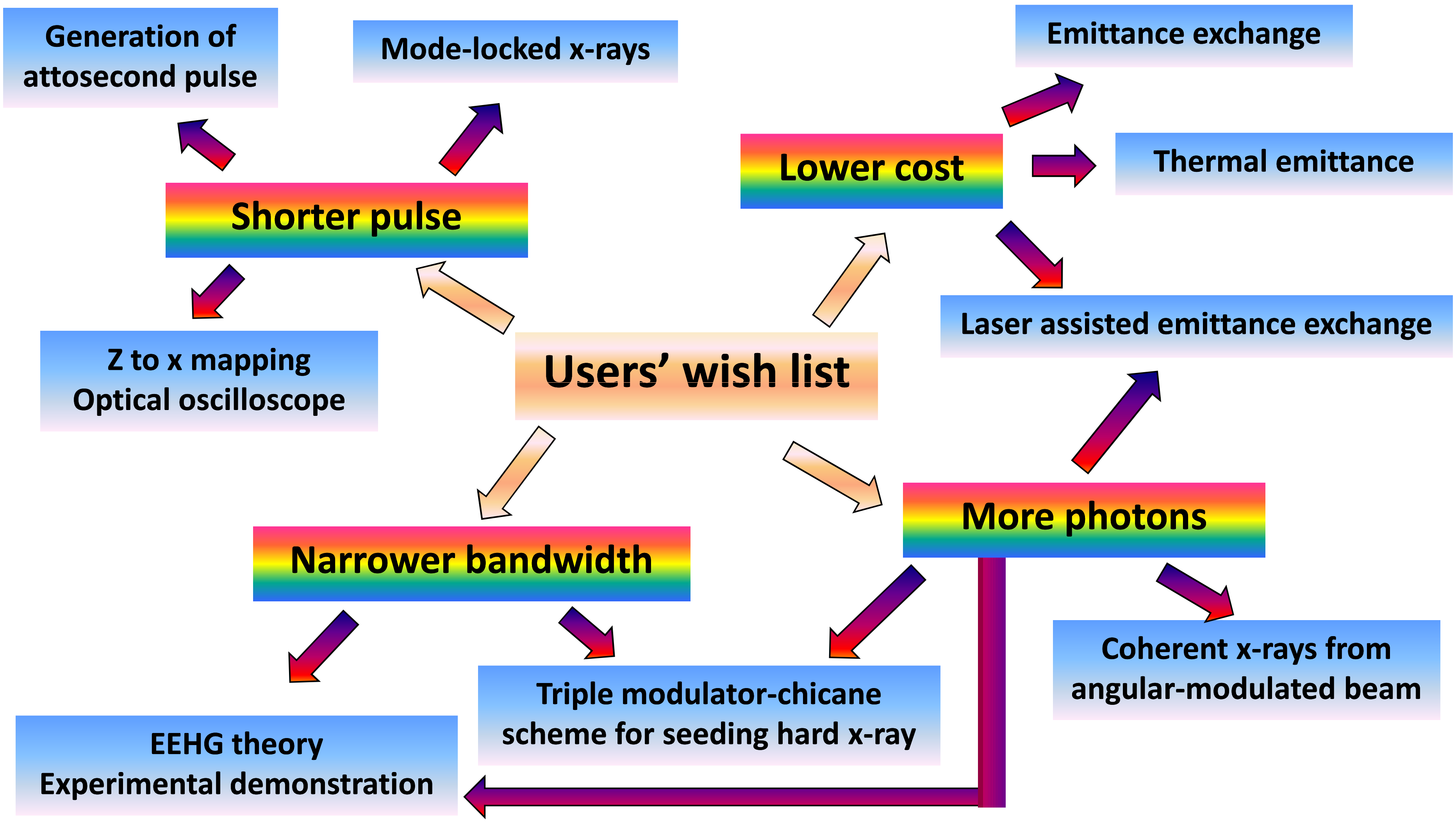


$$n \approx \frac{\Delta y'}{\sigma_y'}$$



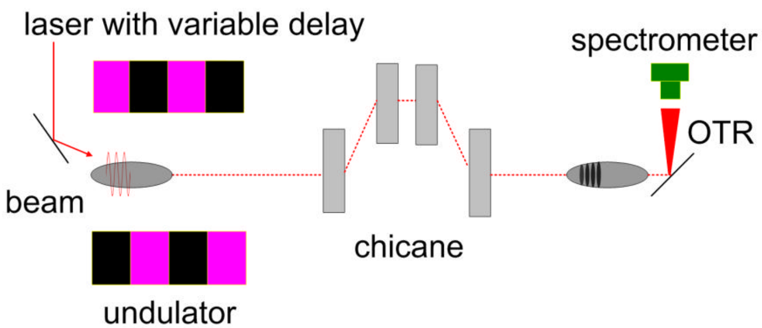
Xiang and Wan, PRL, 104, 084803 (2010)

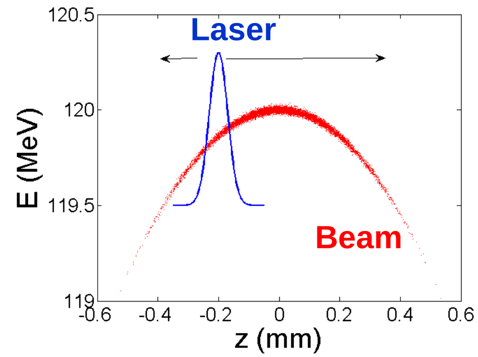
Research summary



Ongoing research (FY12)

- Laser-sampling of beam longitudinal phase space



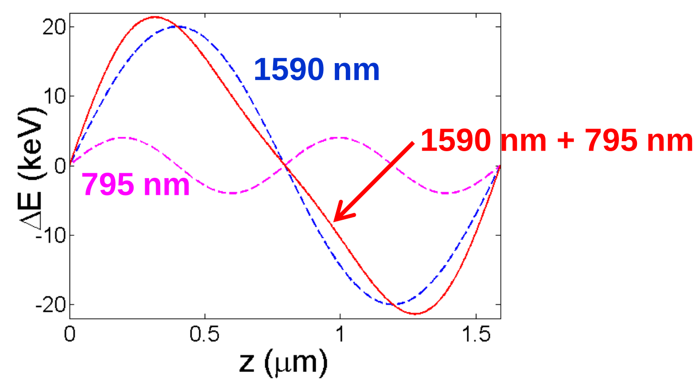


COTR -> current²

λ_{COTR} -> chirp

- Narrow-band THz radiation from laser-modulated beam
- Optical linearizer

Using 795 nm laser to linearize the modulation from a 1590 nm laser



- Emittance exchange with chicane-type beam line
- Mode-locked multichromatic x-rays at LCLS

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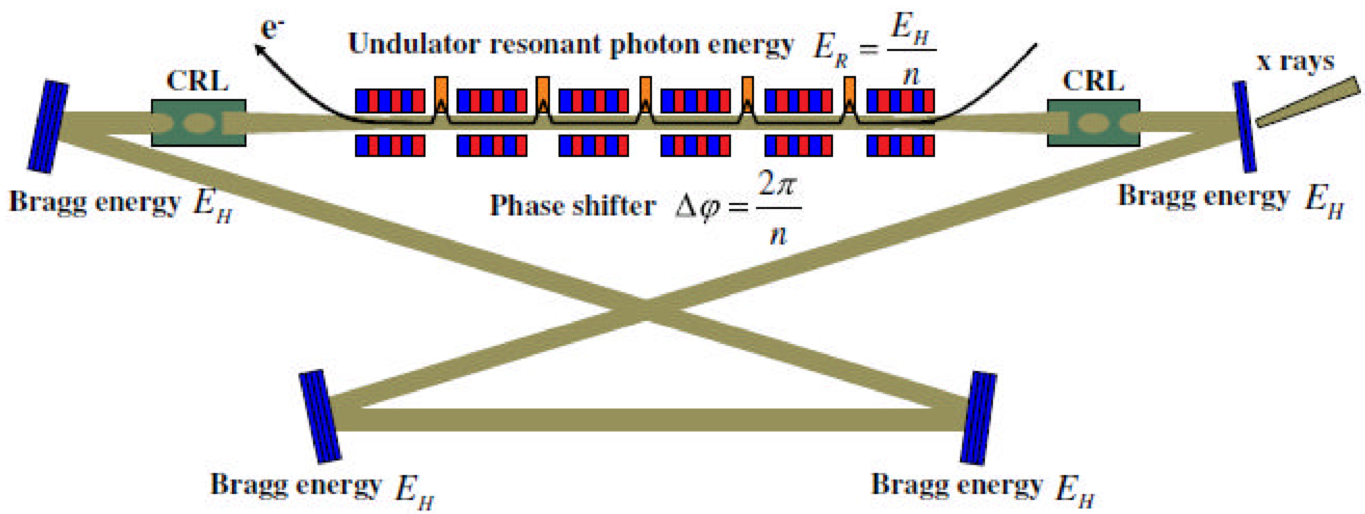
Future research (after FY12)

- Integrate ERL with FEL
  - Oscillator working in the harmonic lasing mode



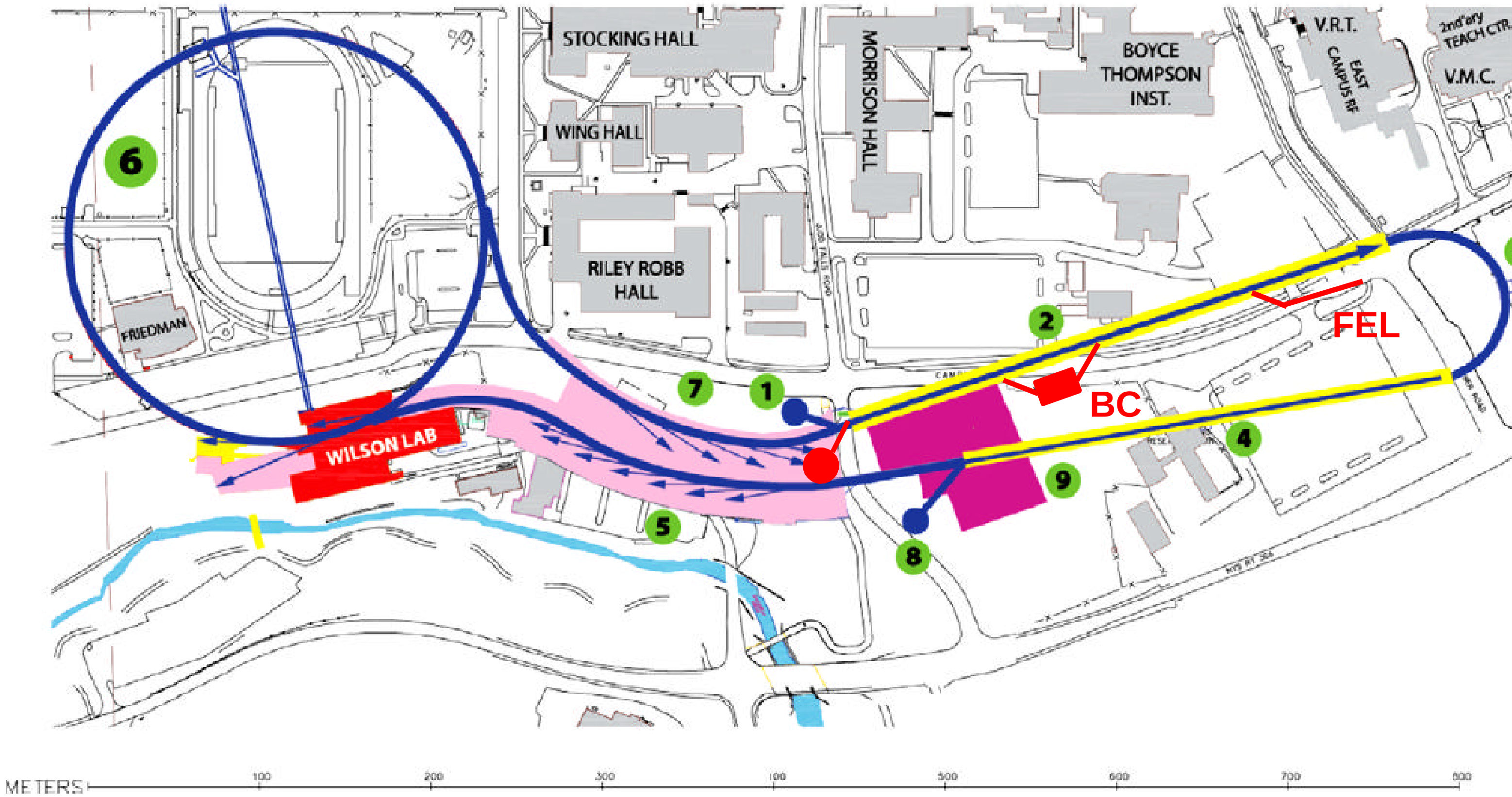
Kim et al., PRL 100, 244802 (2008)
Dai et al., PRL 108, 034802 (2012)

5 GeV, 20 pC, 20A, 0.08 µm -> Lasing at 8~40 keV possible

- Using 'optical linearizer' to pack electrons into tight nano-bunches; Realize FEL with low-current beam and no exponential gain is needed

Future research (after FY12)

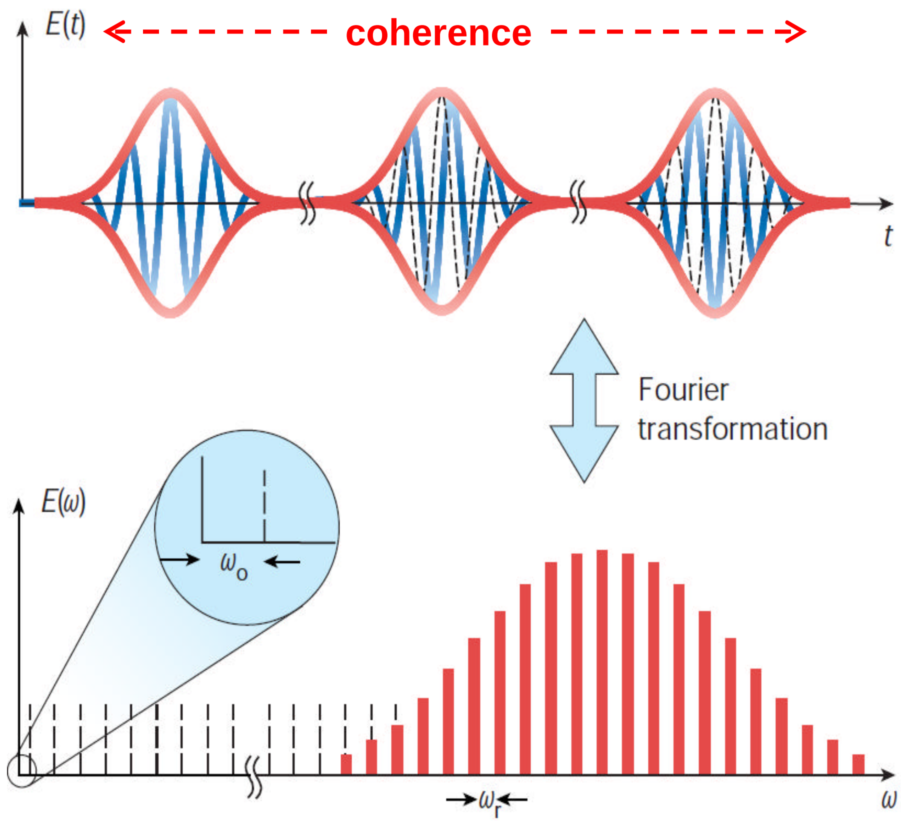
- Integrate ERL with FEL
  - A bypass line dedicated for FEL

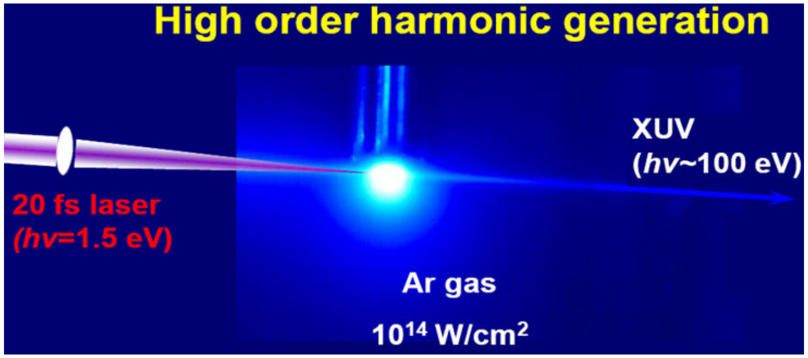


Bilderback *et al., NJP 12, 035001 (2010)*

Future research (after FY12)

- **Develop new concepts for enhancing light source capability**
  - **X-ray frequency comb enabled by high rep-rate laser & beam**

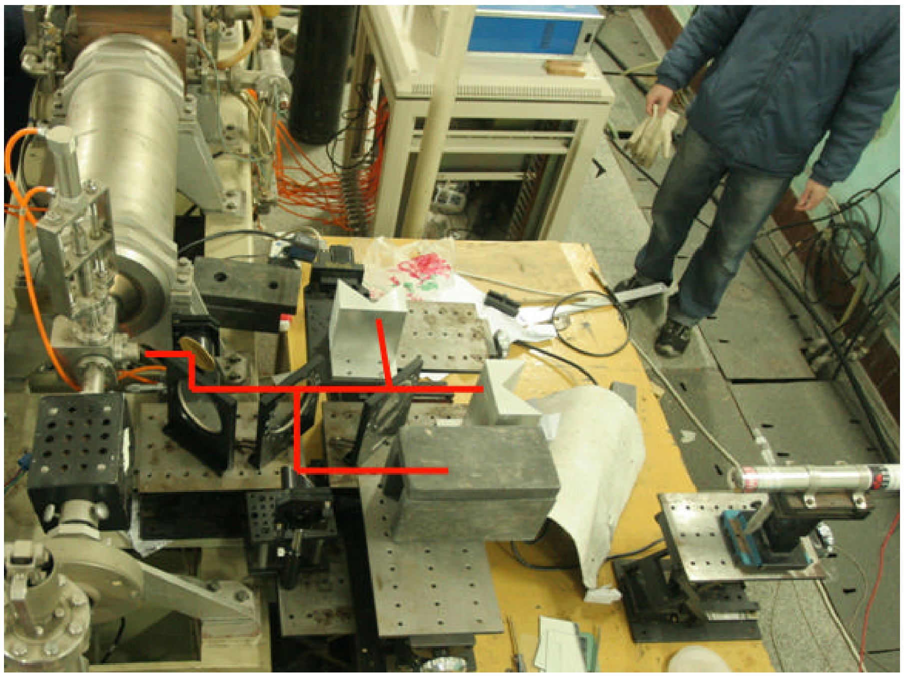




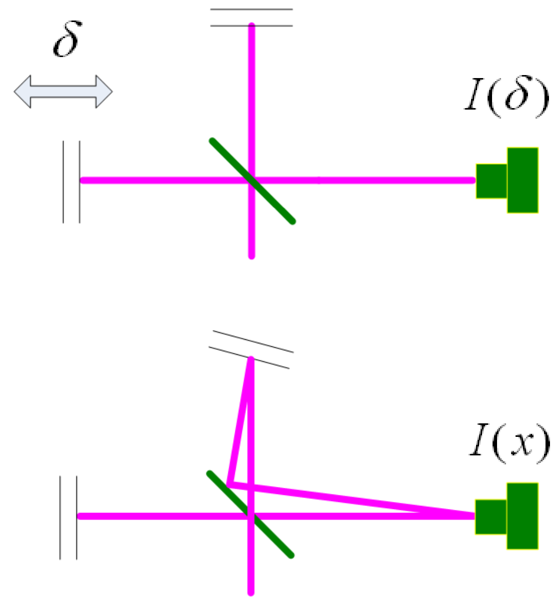
T. Hansch et al., PRL 84, 3232 (2000) *J. Hall et al., PRL 84, 5102 (2000)*	**Optical**
PRL 94, 193201 (2005) *Nature 436, 234 (2005)*	**266 nm**
Opt. Lett 36, 2026 (2011) *Nature 482, 68 (2012)*	**51 nm** **40 nm**
……	**a few nm**

Future research (after FY12)

- **Advanced beam diagnostics**
  - **Non-invasive beam characterization with optical diffraction radiation**
  - **Non-invasive bunch length measurement with a single-shot interferometer**

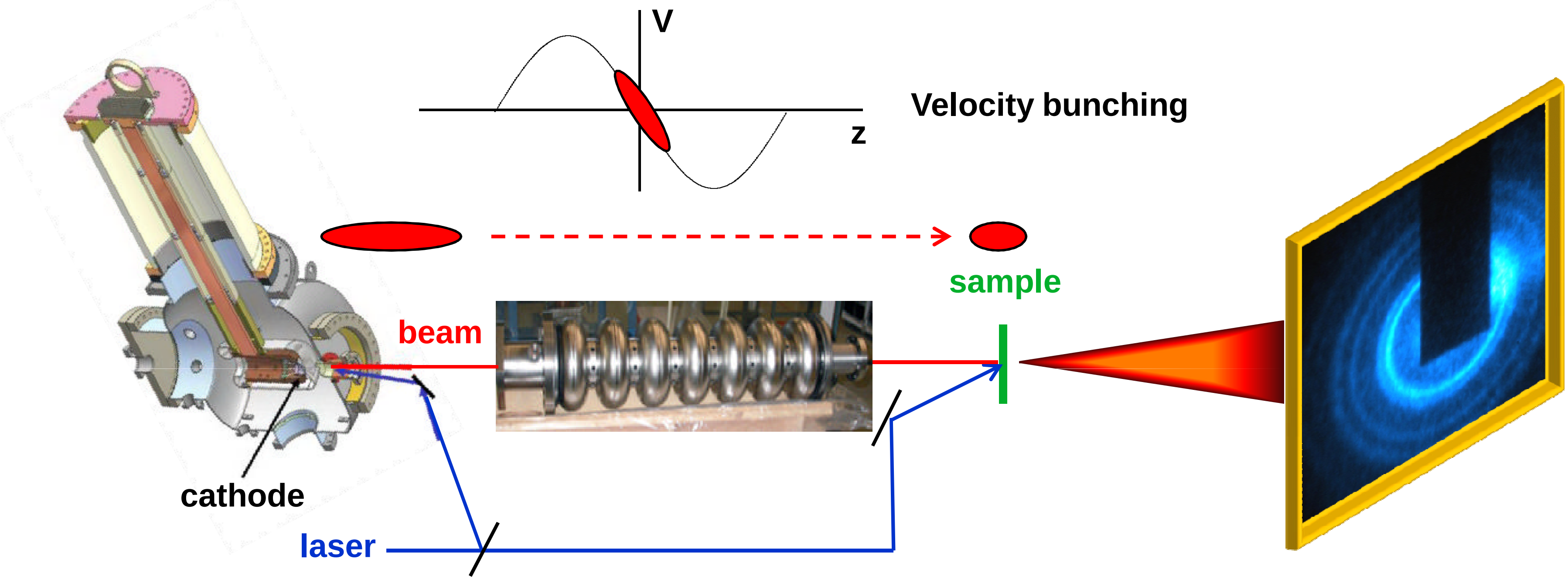


D. Xiang, Ph.D thesis, 2008



Future research (after FY12)

- Ultrafast electron diffraction (UED) with an ERL gun



  - 10~100 times higher energy than conventional UED
  - 1000000 times higher repetition rate than relativistic UED
  - Open up new opportunities for UED, electron crystallography
- Understand an ERL injector in more detail

Summary

- Accelerator physics becomes cute in 21st century
- New opportunities enabled by accelerator based light source

  ----- Capture the ultrafast and probe the ultrasmall
- Realizing the next generation x-ray light sources requires extensive R&D in accelerator physics
  - Generation and preservation of high brightness beam
  - Advanced techniques for beam manipulation and diagnostics
- Marrying laser and electron beams will trigger new concepts and benefit accelerator/laser/user communities

'The state-of-the-art light source facility of the future will include a complete marriage of accelerator principles and laser art'
------from a panel on novel light source initiated by the US DOE

Many thanks to my colleagues and the Echo-7 team!

Thank you!

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