Demonstration of the Echo-Enabled Harmonic Generation (EEHG) Technique for Seeding FELs

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March-29-2011

Particle Accelerator Conference, 2011, New York

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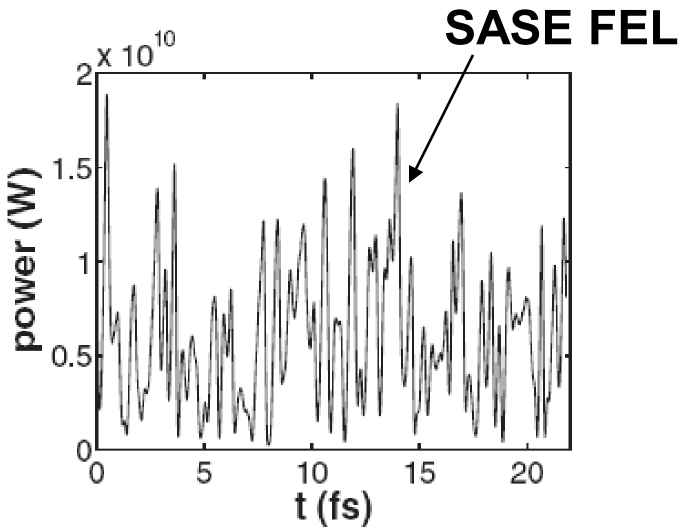
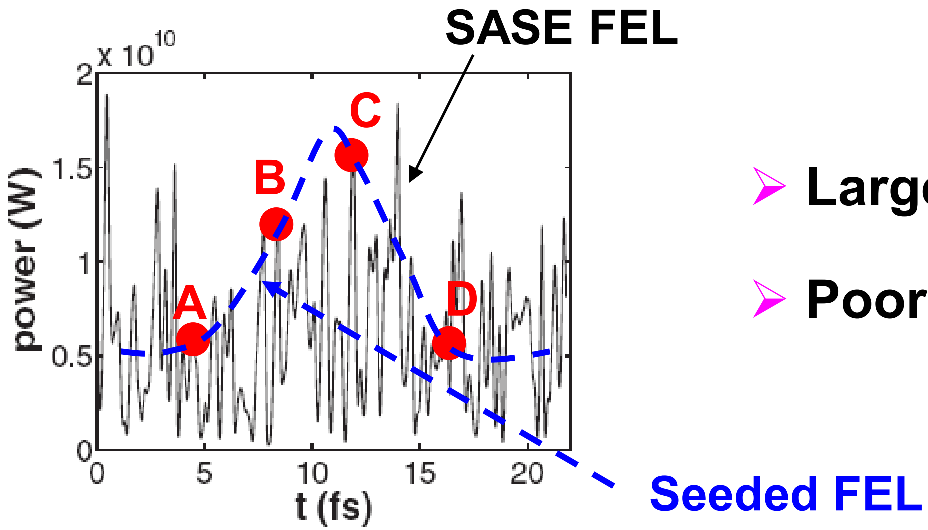
Why seeded FELs?



- Large statistic fluctuations
- Poor temporal coherence

- Many applications that require (or could benefit from) improved temporal coherence
- Seeding with external laser pulse
  - Fully coherent FEL pulse
  - Well-defined timing
  - Less undulators to reach saturation

Why seeded FELs?



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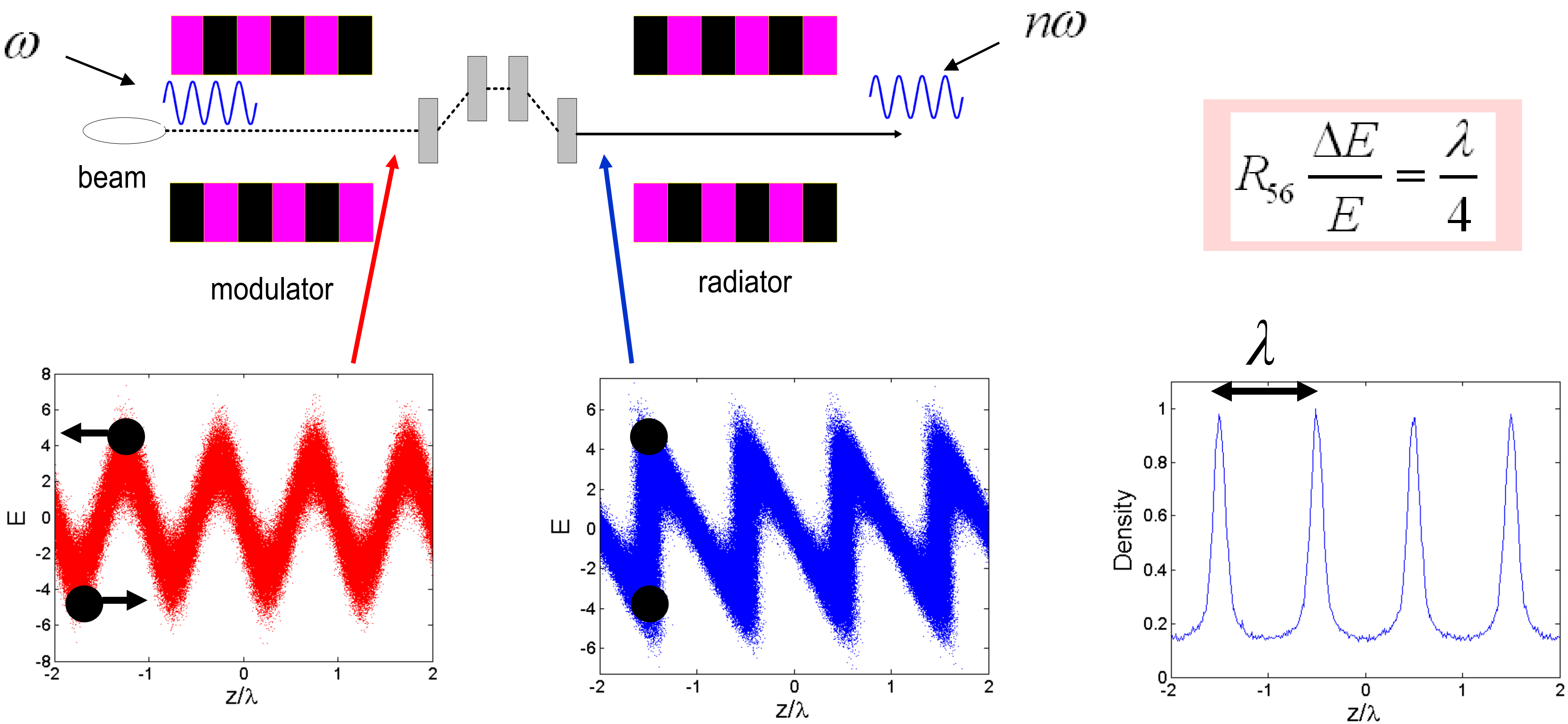
Classical external seeding (HGHG)

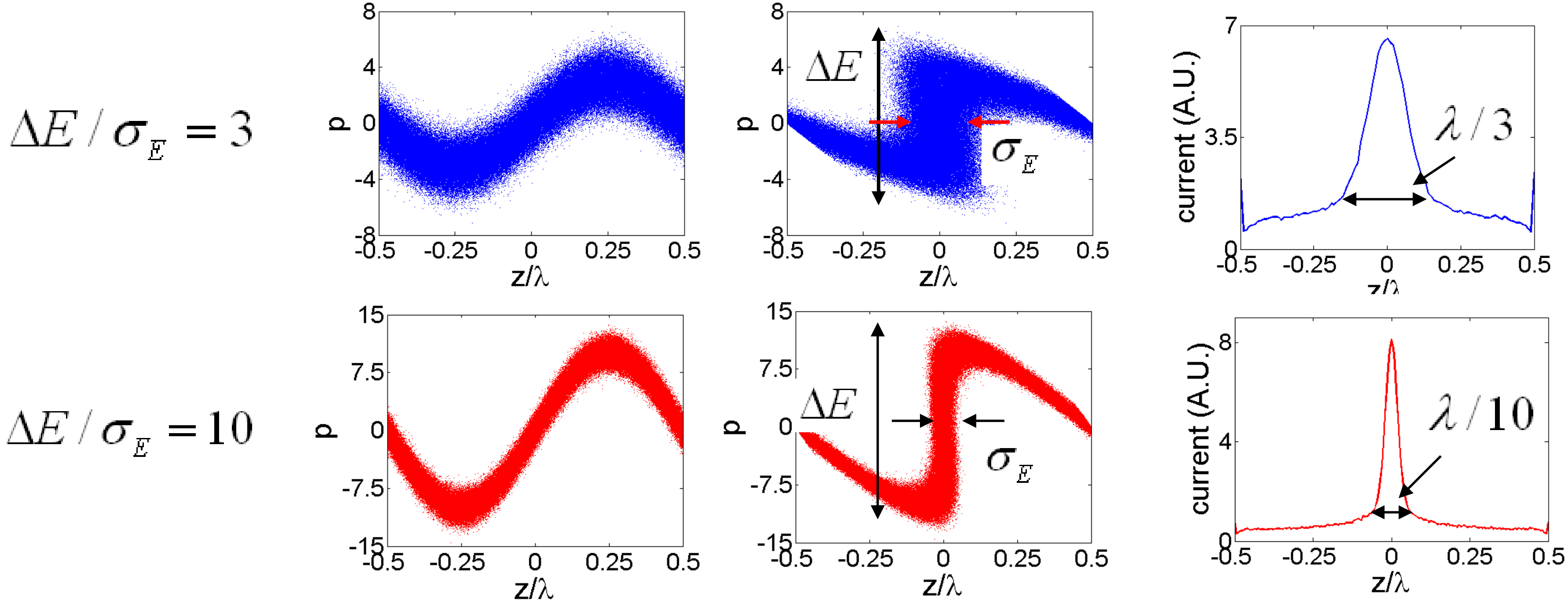


$$R_{56}\frac{\Delta E}{E}=\frac{\lambda}{4}$$

- **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**

Limitations

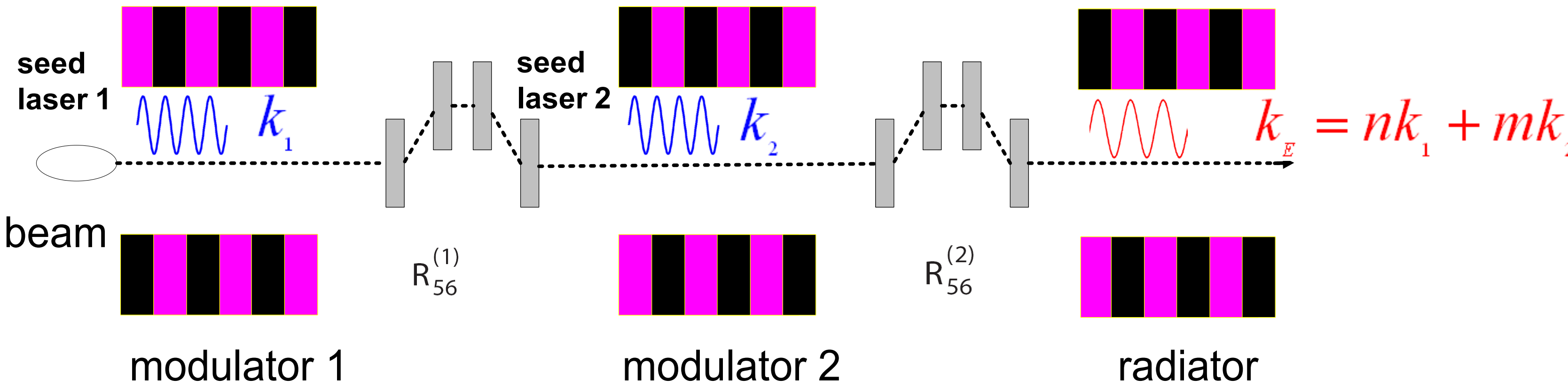
- **Low up-frequency conversion efficiency:** $\Delta E / \sigma_E \approx n$



Modulator exit **Chicane exit** **Current distribution**

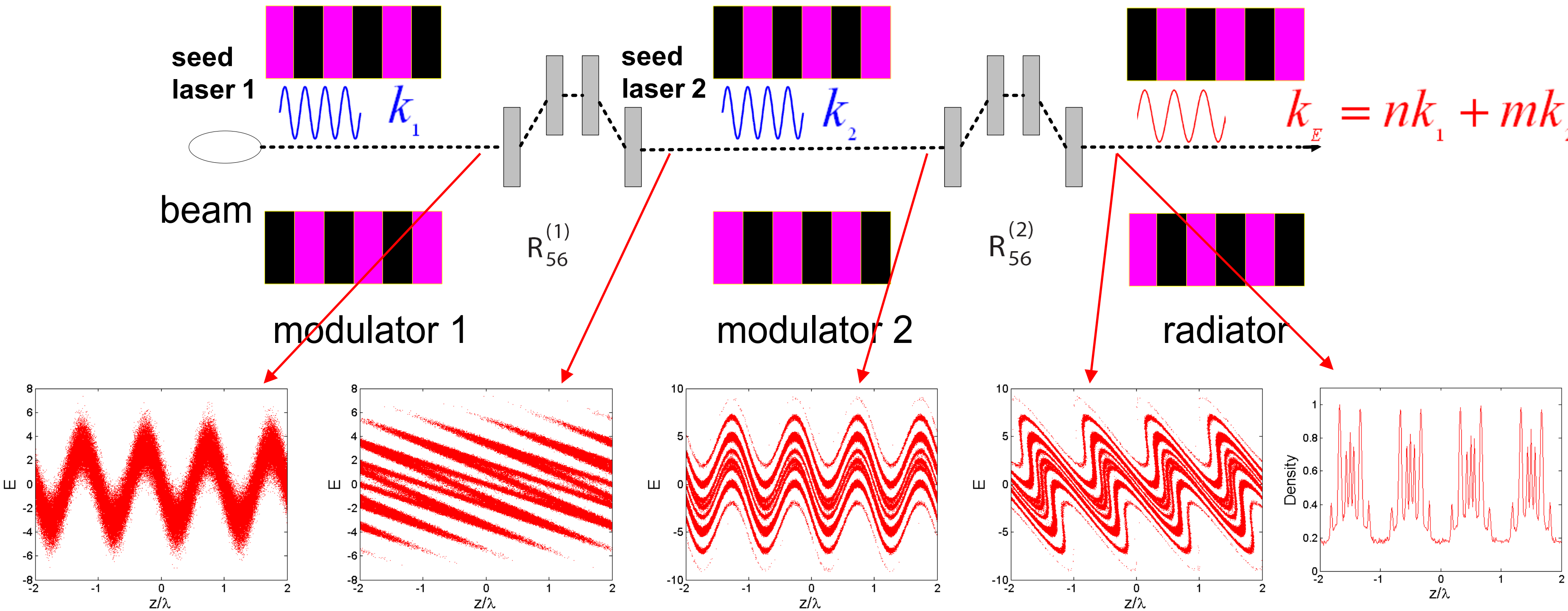
- **Outcome: Bunching (large ΔE) OR Gain (small ΔE)**
- **But seeded FEL wants: Bunching AND Gain**

EEHG FEL



seed laser 1
k_1
seed laser 2
k_2
$k_E = nk_1 + mk_2$
beam
$R_{56}^{(1)}$
$R_{56}^{(2)}$
modulator 1
modulator 2
radiator

EEHG FEL



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

EEHG FEL: Promises and Challenges

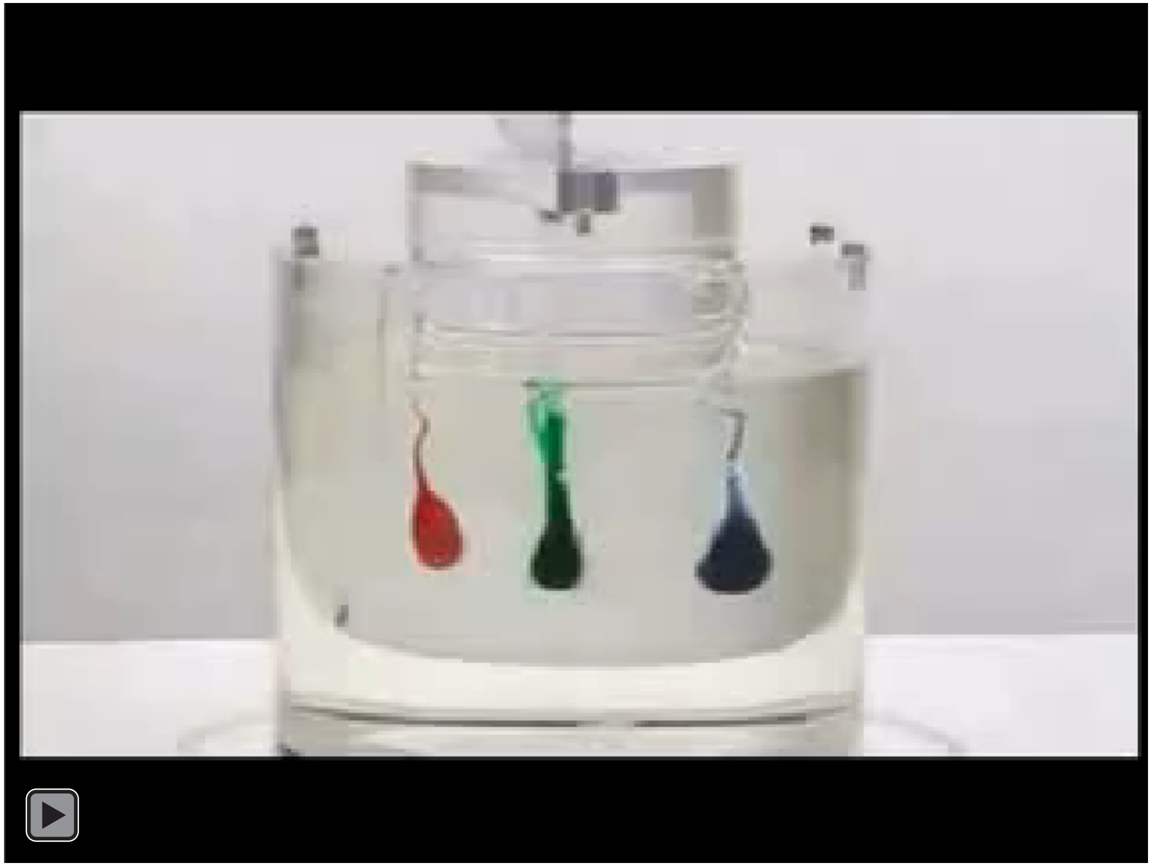
Promises

- Remarkable up-frequency conversion efficiency: $b_n \sim n^{-1/3}$
- Bunching AND Gain
- UV laser -> soft x-rays in a single stage possible
- Wide interest: China / France / Italy / Switzerland / UK / USA

Challenges

- Preservation of long-term (~ns) memory of phase space correlations
- CSR/ISR in chicanes
- Quantum diffusion in undulators
- Unwanted x-z coupling
- Path length difference for particles with different betatron amplitude

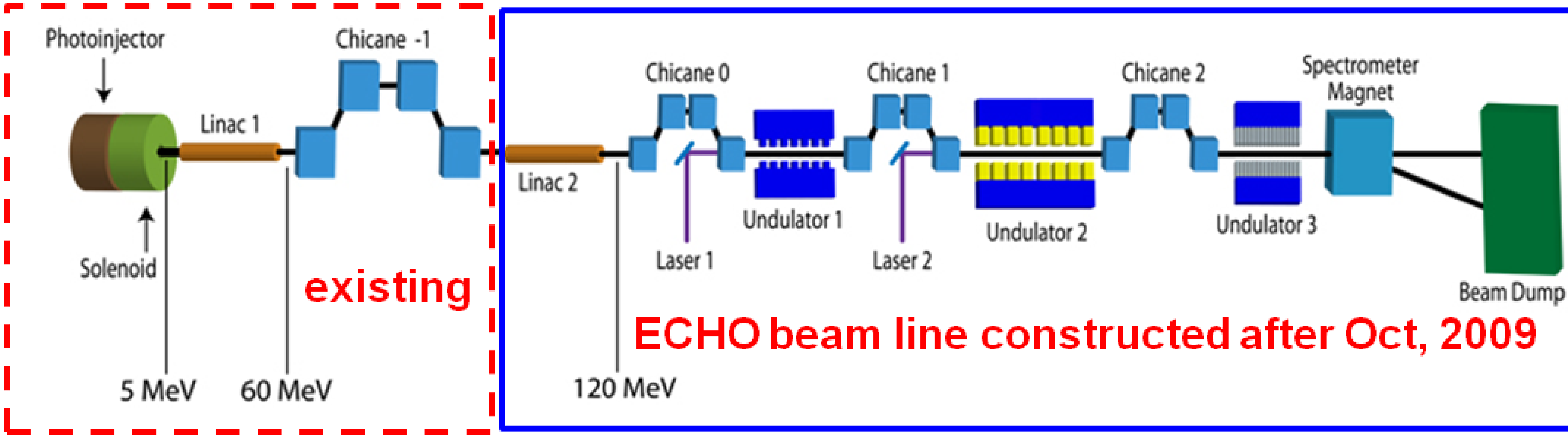
Preserve long-term memory



- 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
- Need experimental demonstration (SLAC & SINAP)

Courtesy of 'Youtube' and D. Ratner

ECHO experiment at NLCTA



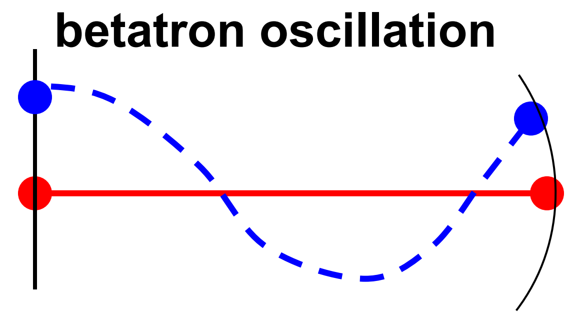
- **To-do-list**
  - **Additional lianc to boost beam energy from 60 MeV to 120 MeV**
  - **3 chicanes + 3 undulators**
  - **Quadrupoles, correctors, power supplies**
  - **Laser systems and laser transport**
  - **OTR, YAG, UV spectrometer, DAQ ……**

Road to ECHO

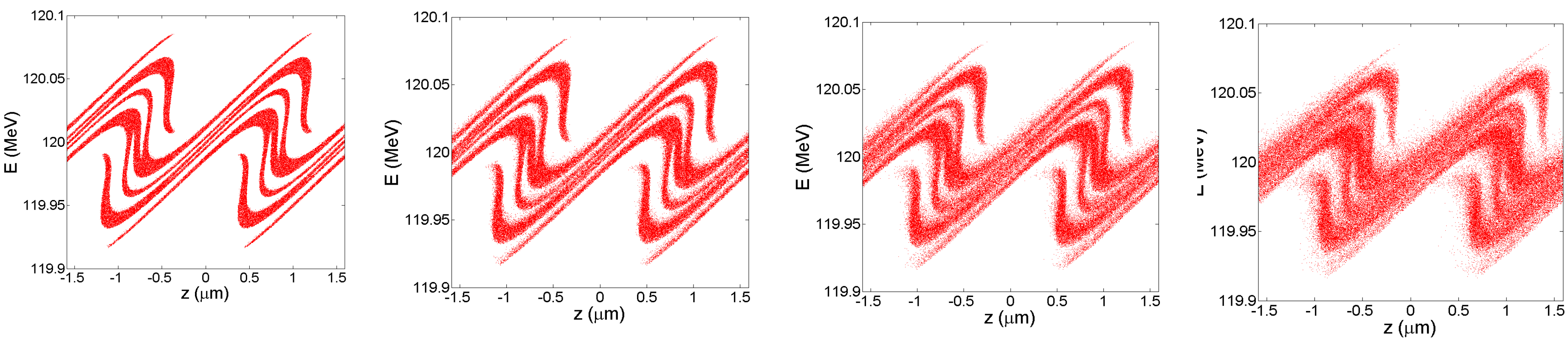
- **03-2009: First planning meeting**
- **06-2009: CD&TD finished and LDRD funded**

Conceptual design

$$z = z_0 + R_{56}\delta_0 + R_{51}x_0 + R_{52}x_0' + T_{566}\delta_0^2 + T_{511}x_0^2 + T_{521}x_0x_0' + T_{522}x_0' + T_{533}y_0^2 + T_{543}y_0y_0' + T_{544}y_0'$$



- Lattice optimized to preserve fine structures



1 mm mrad | 4 mm mrad | 8 mm mrad | 16 mm mrad

- Tolerance on field errors and alignment errors quantified through extensive simulations
- Possible risks identified and back-up plans prepared

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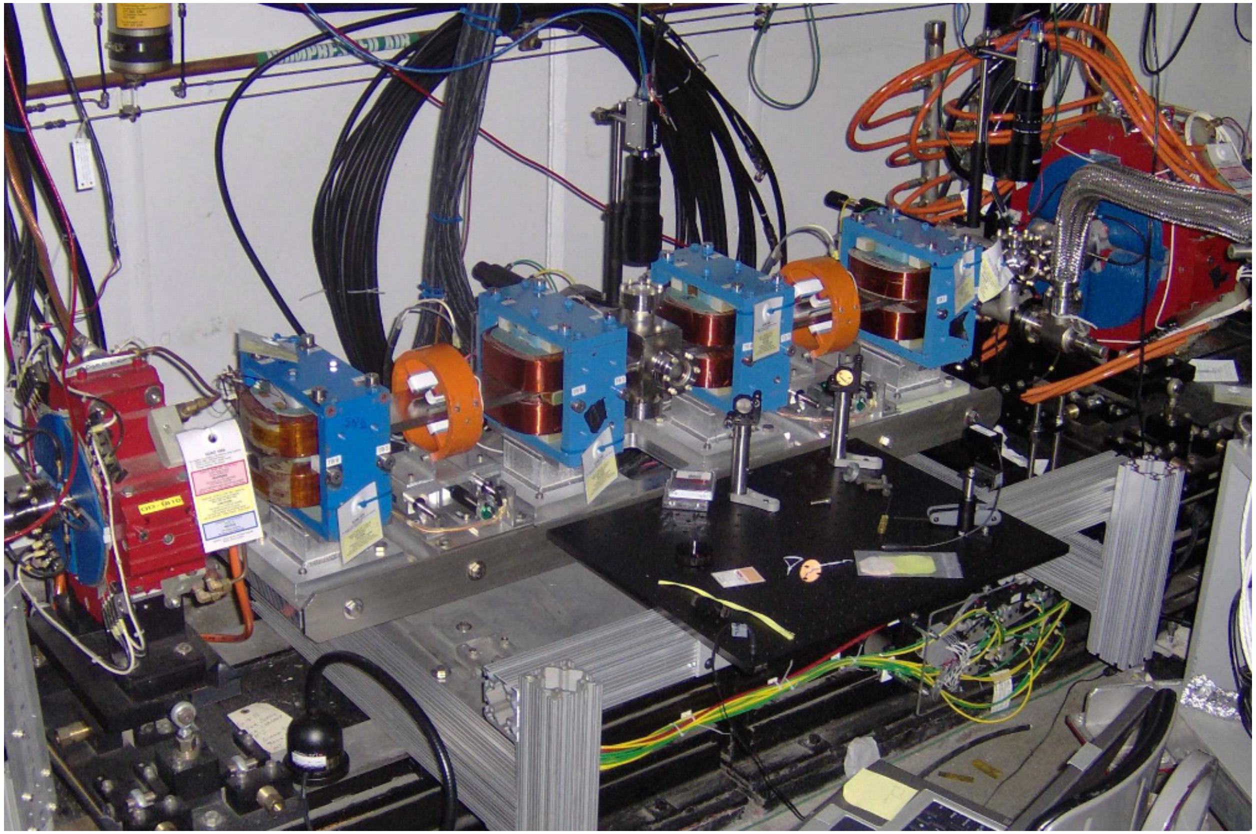
- **09-2009: BES funding arrived / First chicane installed**

First chicane installed

- Dipoles from SLC spare correctors
- 14 dipoles constructed and 12 selected for 3 chicanes



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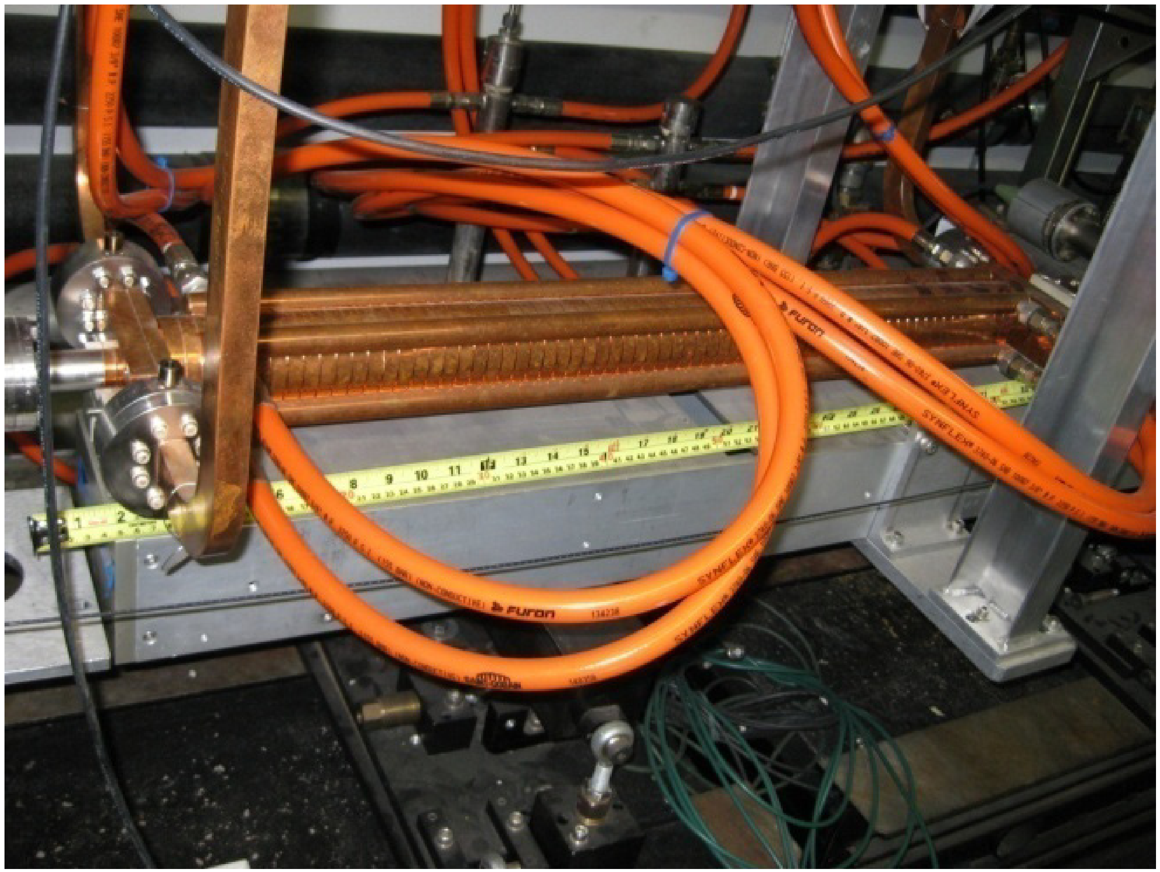
- 12-2009: 120 MeV beam achieved

120 MeV achieved

- A 75 cm X-band structure to provide 60 MeV gain
- World's highest-gradient rf structure under normal operation



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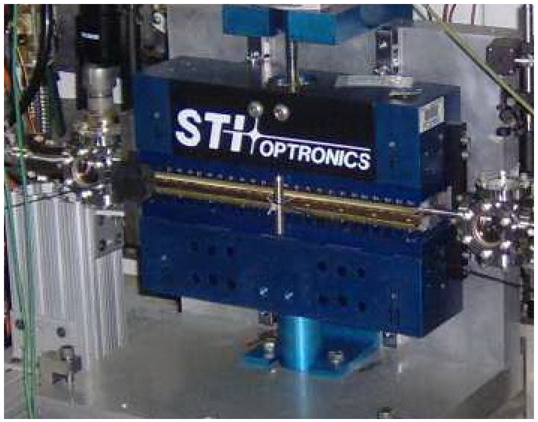
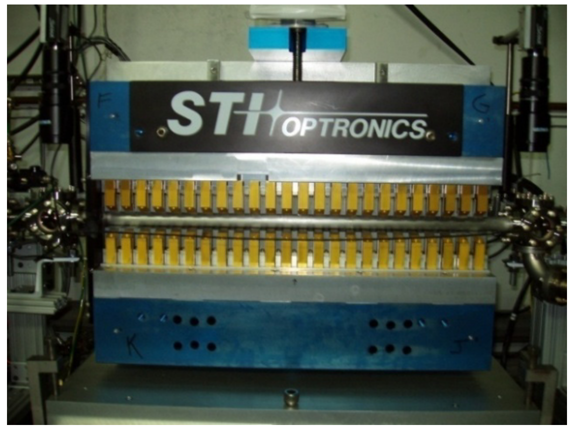
- 02-2010: First undulator installed

Undulators installed

- **Two from STI-Optronics and one from LBNL**

10 × 3 cm | **10 × 5.5 cm** | **10 × 2 cm**





$$x' = \frac{e}{\gamma mc}\int_{-\infty}^{z} B_y dz = \frac{1}{3.34P(\mathrm{GeV/c})}\int_{-\infty}^{z} B_y dz(\mathrm{T\cdot m})$$

First field integral < 10 Gcm, corresponding to x'<25urad.

$$x = \frac{e}{\gamma mc}\int_{-\infty}^{z} B_y dzdz = \frac{1}{3.34P(\mathrm{GeV/c})}\int_{-\infty}^{z} B_y dzdz(\mathrm{T\cdot m^2})$$

Second field integral < 1000 $\mathrm{Gcm^2}$, corresponding to x<25um.

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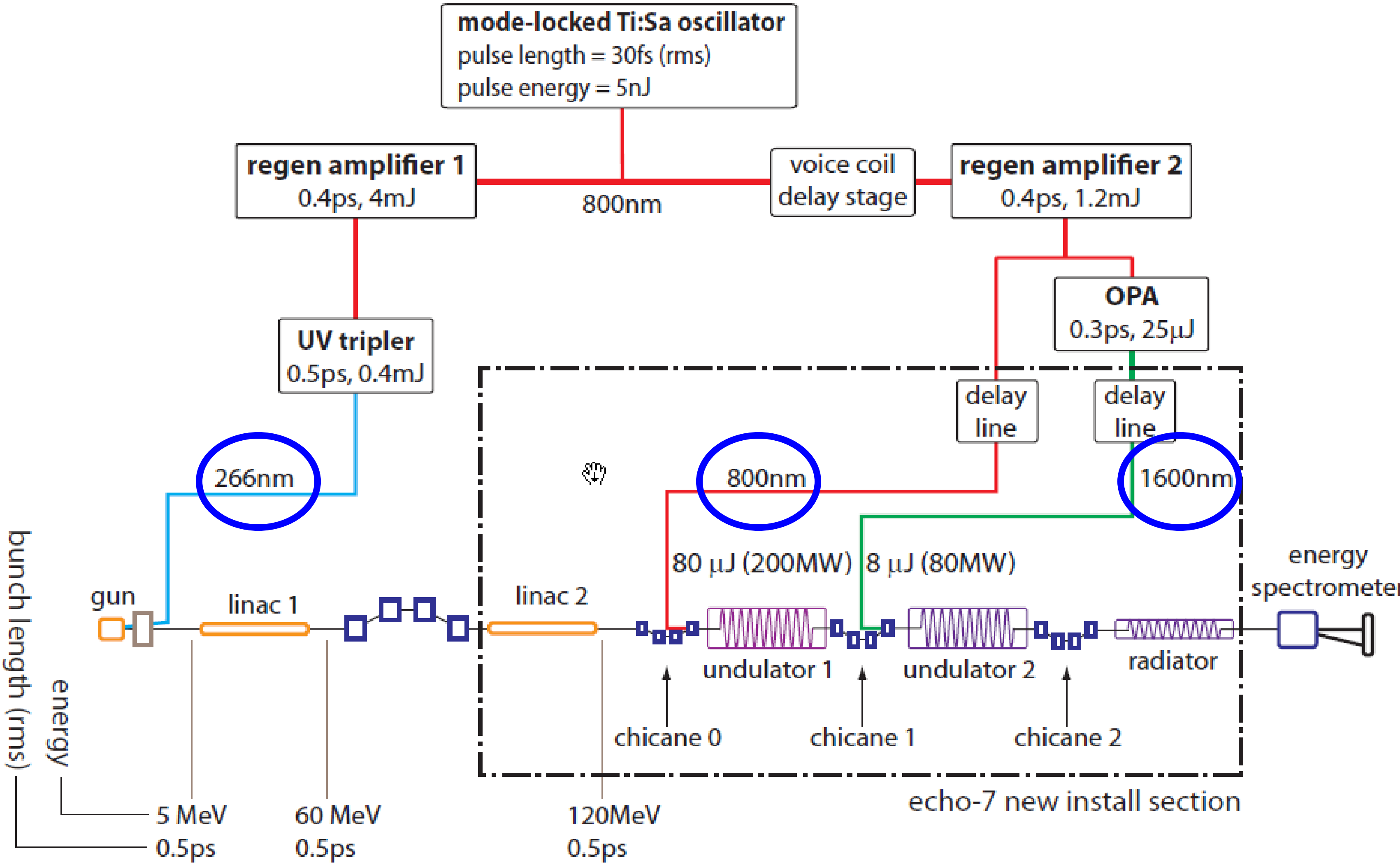
- **04-2010:** Electron-laser (795 nm) interaction achieved

Laser systems



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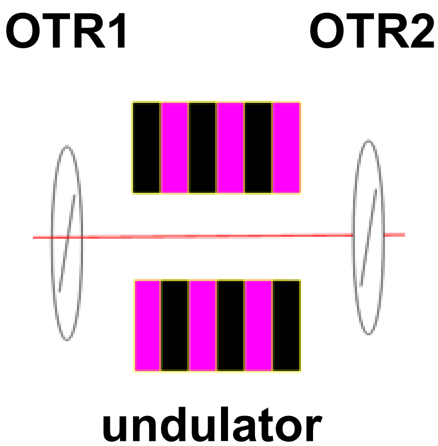
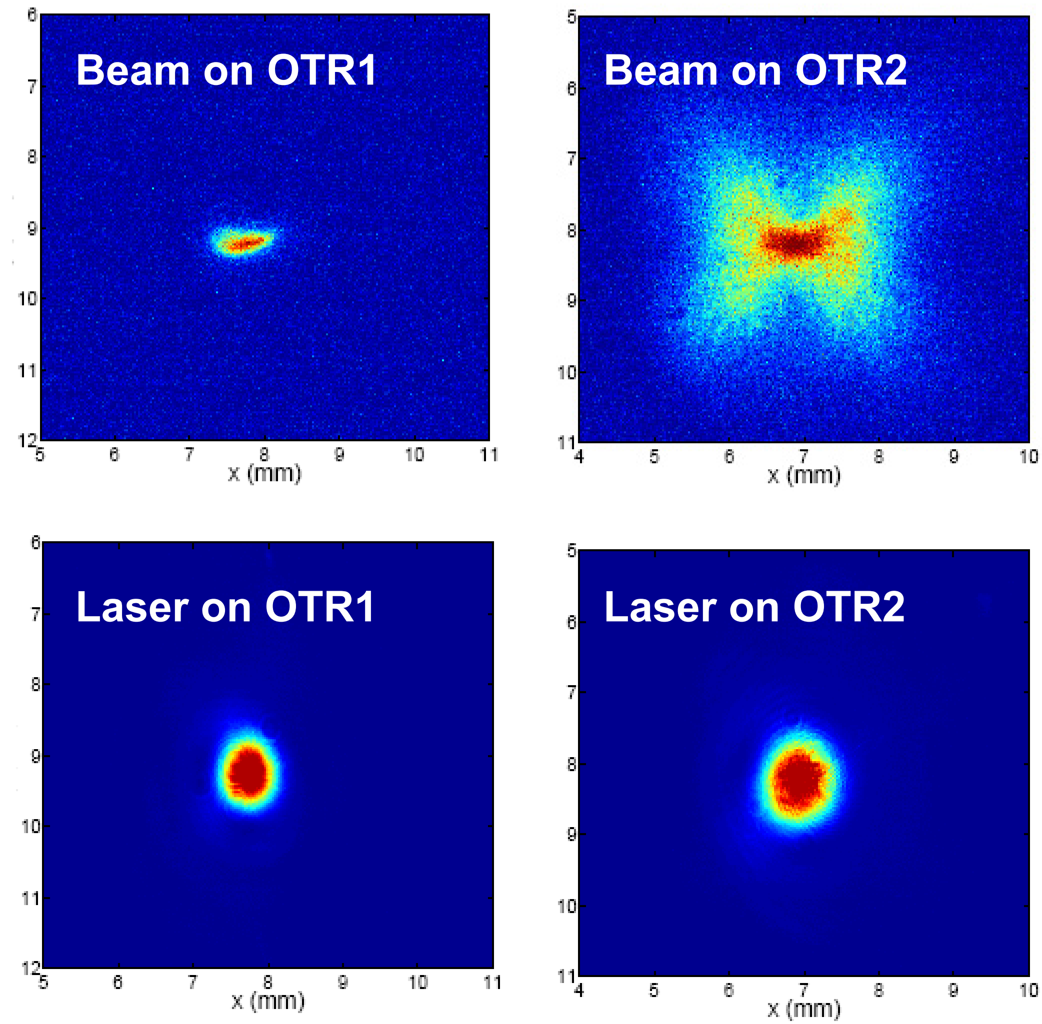
Laser-electron interaction achieved

- **Spatial overlap**



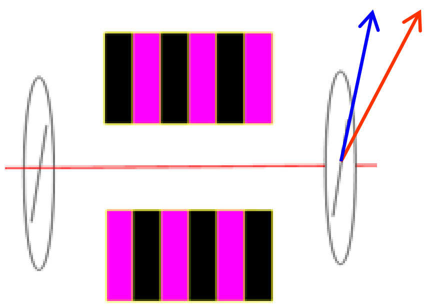
Beam-laser spatial overlap is achieved by steering the laser to the same position as the electron beam on the OTR screens upstream and downstream of the undulators



Laser-electron interaction achieved

- ❖ **Temporal overlap**

  to a photodiode



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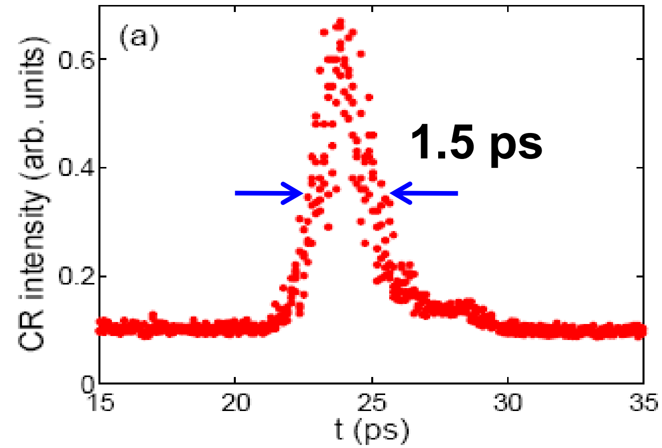
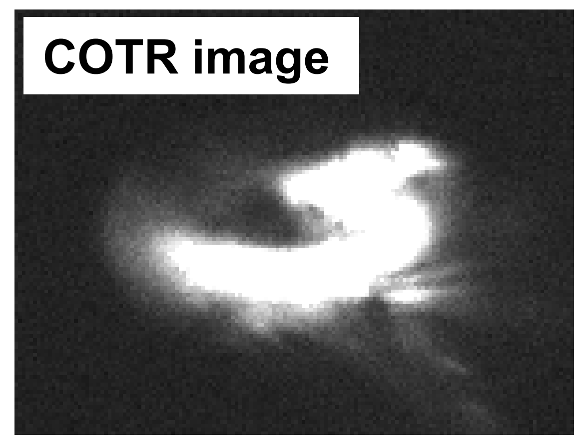
➢ **The laser and undulator radiation are reflected out by the OTR screen and detected by a fast photodiode.**

➢ **Scan delay stage to finely adjust the laser timing until the COTR enhancement is observed.**



COTR signal vs laser timing



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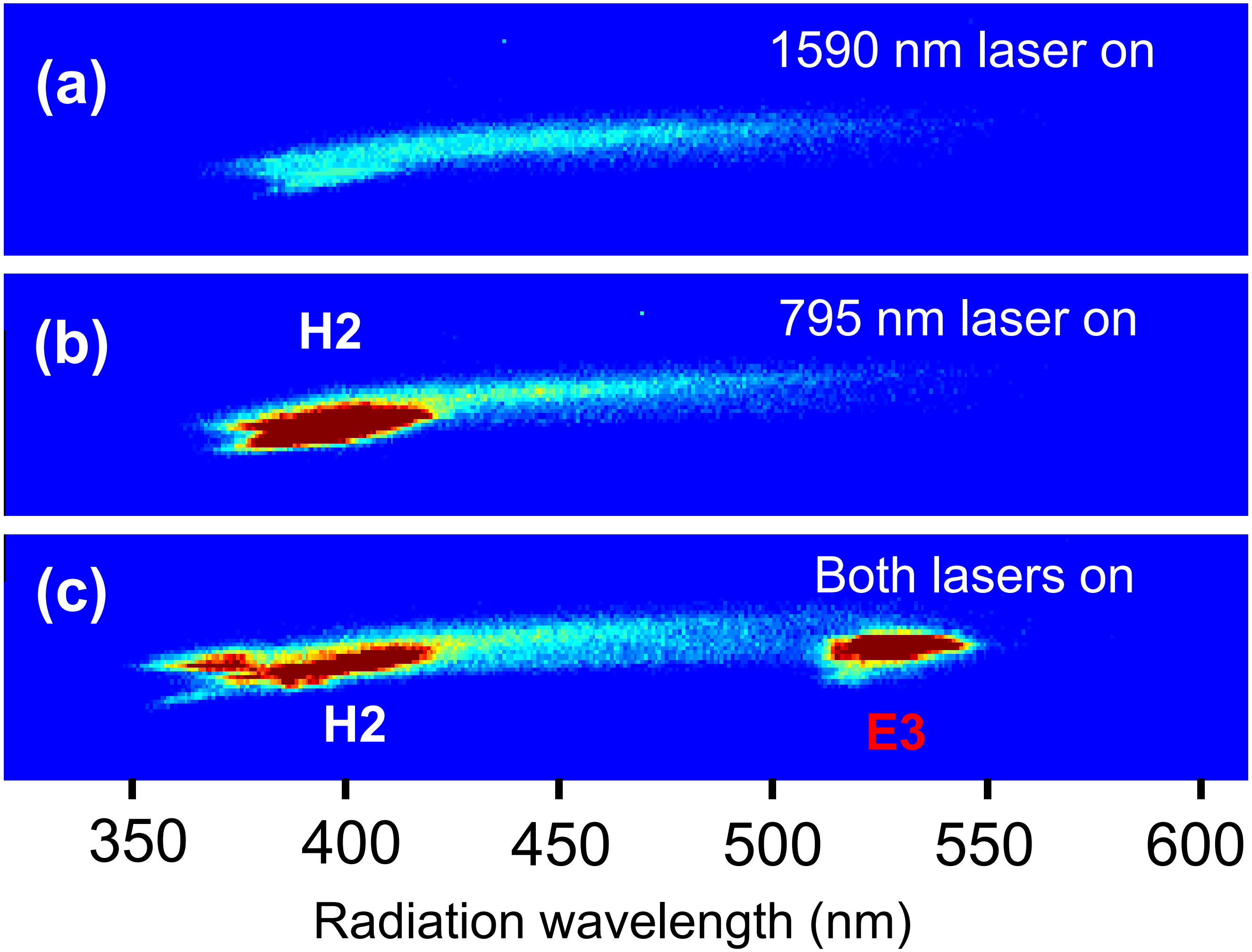
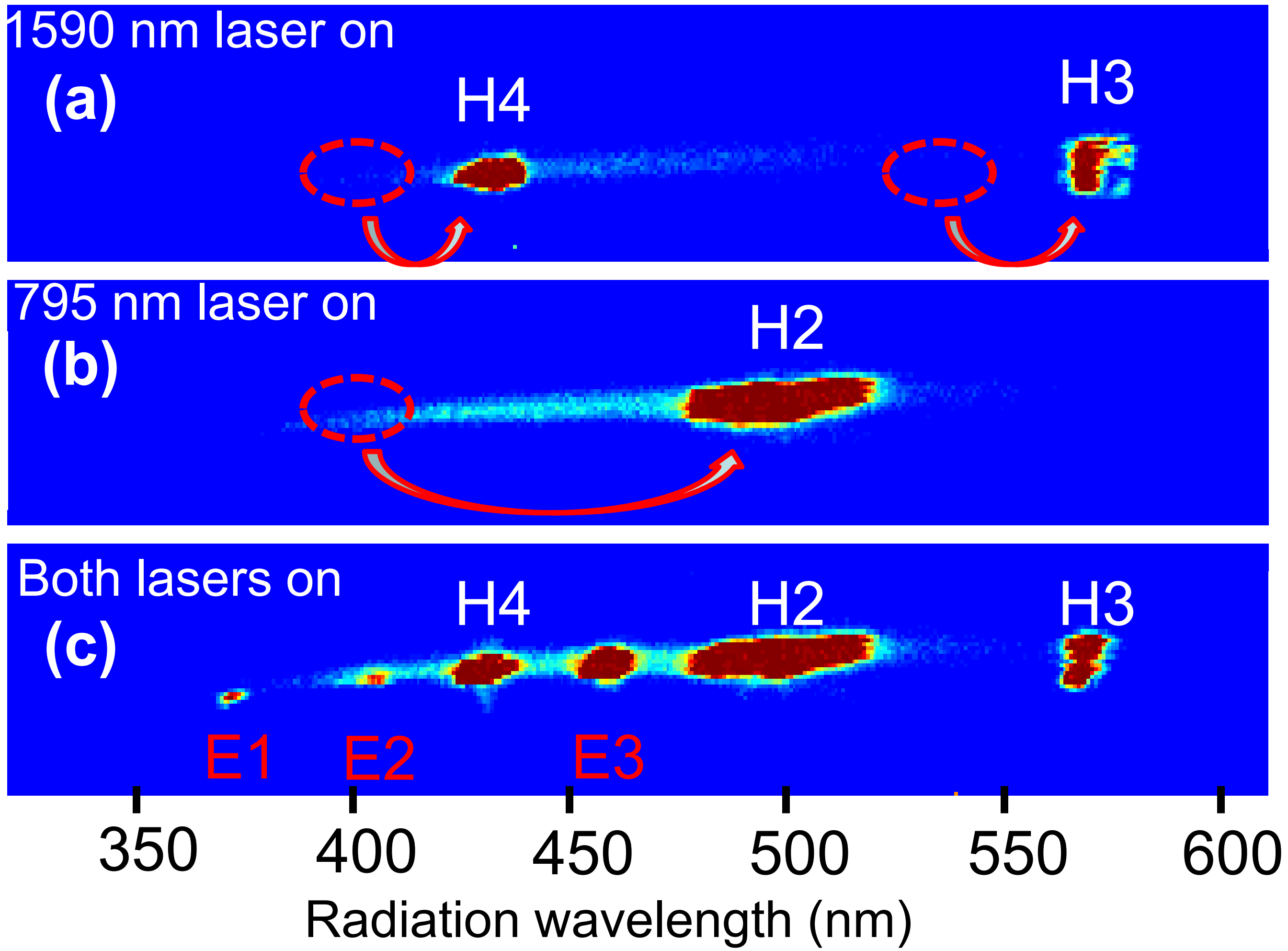
- 12-2009: 120 MeV beam achieved
- 02-2010: First undulator installed
- 04-2010: Electron-laser (795 nm) interaction achieved
- 05-2010: Electron-laser (1590 nm) interaction achieved
- 05-2010: First harmonic radiation signal (EEHG+HGHG)
- 07-2010: First unambiguous echo signal

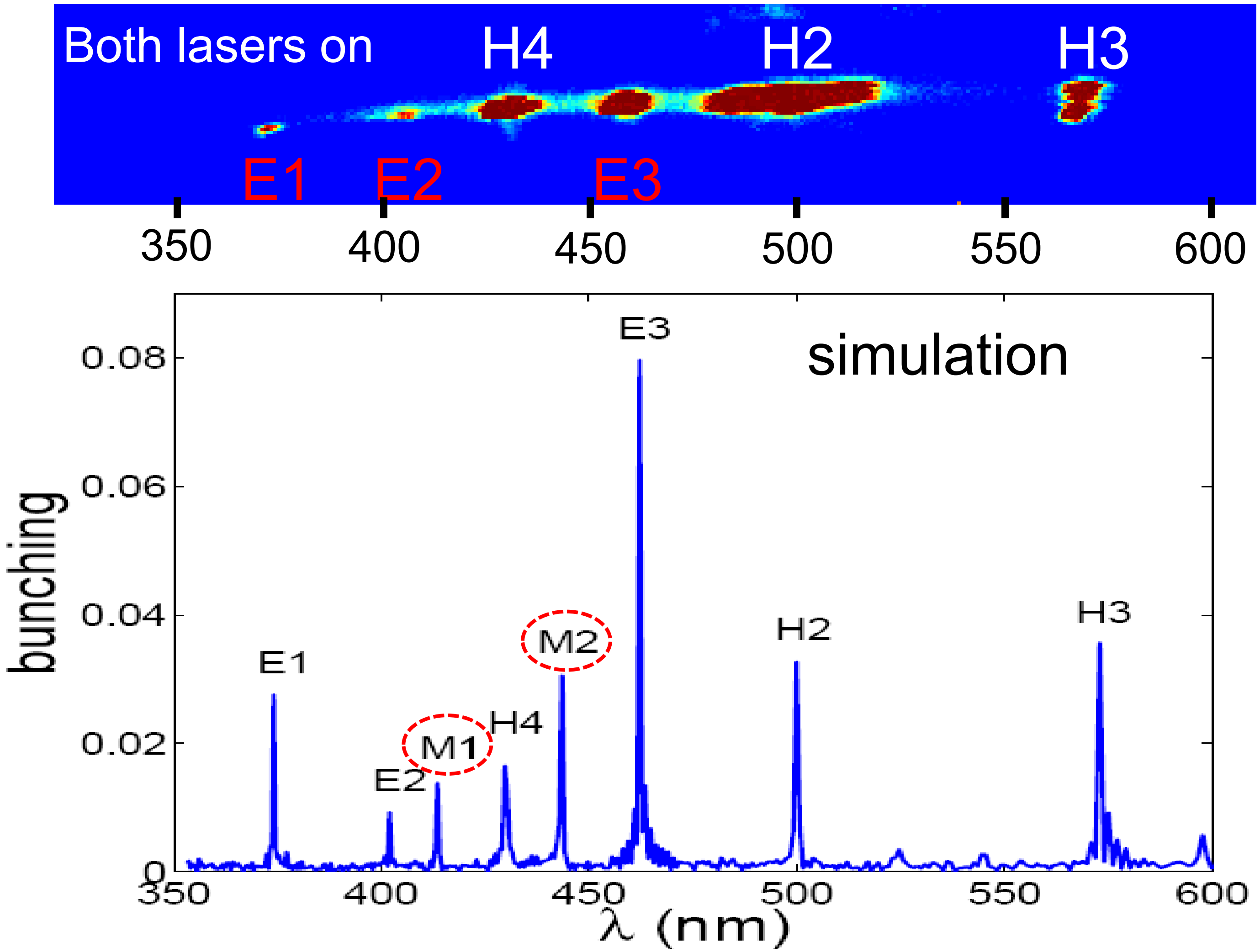
First unambiguous ECHO signal



ECHO signal with chirped beam

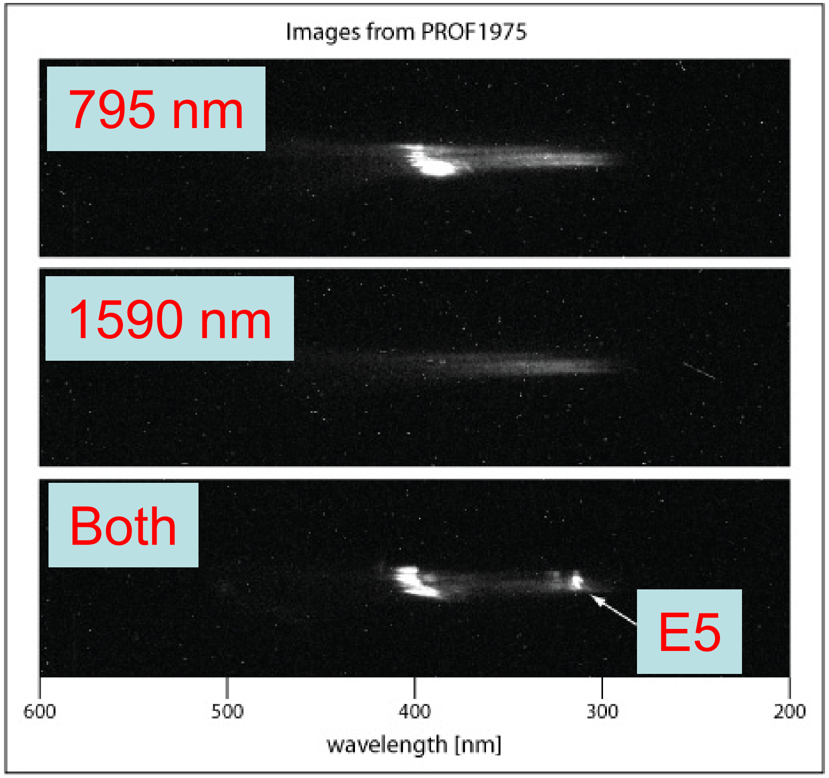


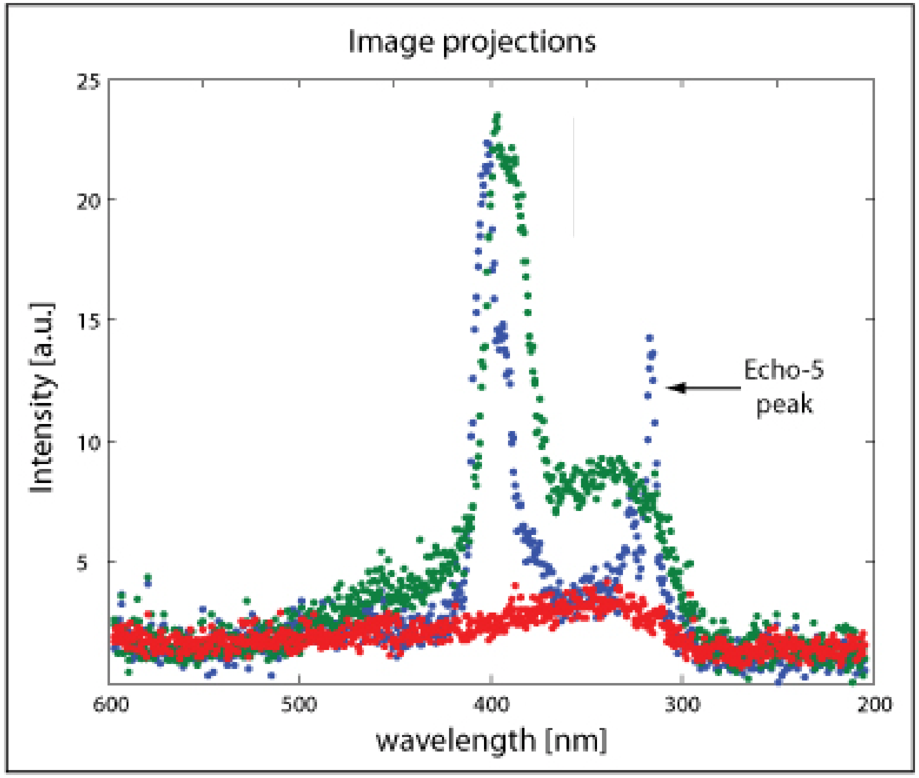
In good agreement with theory



5th harmonic in 01-2011

- Optical lens replaced with UV lens
- Preserving bunching at **318 nm with 120MeV/8um** beam is as difficult as preserving bunching at **3.18 nm with 1.5GeV/1um beam.**





Status and future of ECHO-7

- **What have been done (03-2009 to 01-2011)**
  - **Demonstrated phase space correlations can be preserved**
  - **5th harmonic generated when $\Delta E >> \sigma_E$**
- **What we are doing (03-2011 to 07-2011)**
  - **Increase σ_E from 1 keV to 10~20 keV**
  - **Demonstrate high harmonic (7th) can be generated with $\Delta E \sim \sigma_E$**
  - **Benchmark of EEHG theory**
- **What we hope to do (after 10-2011)**
  - **Ultrahigh harmonics (>15th)**
  - **Demonstrate transform-limited output**
  - **Confirm scaling and identify risks for seeding x-ray FELs**

Summary

- Basic physics of EEHG verified
  - Phase space correlations can be preserved
  - All the experimental observations well explained with EEHG theory
- More exciting results coming soon

Many thanks to the ECHO-7 team and a lot of other people for helpful discussions and commissioning assistance.

This work was supported by the US DOE Office of Basic Energy Sciences using the NLCTA facility which is partly supported by US DOE Office of High Energy Physics.

Thanks!