First Demonstration of a Slippage-dominant Superradiant Free-electron Laser Amplifier

Xi Yang
for NSLS SDL team at BNL
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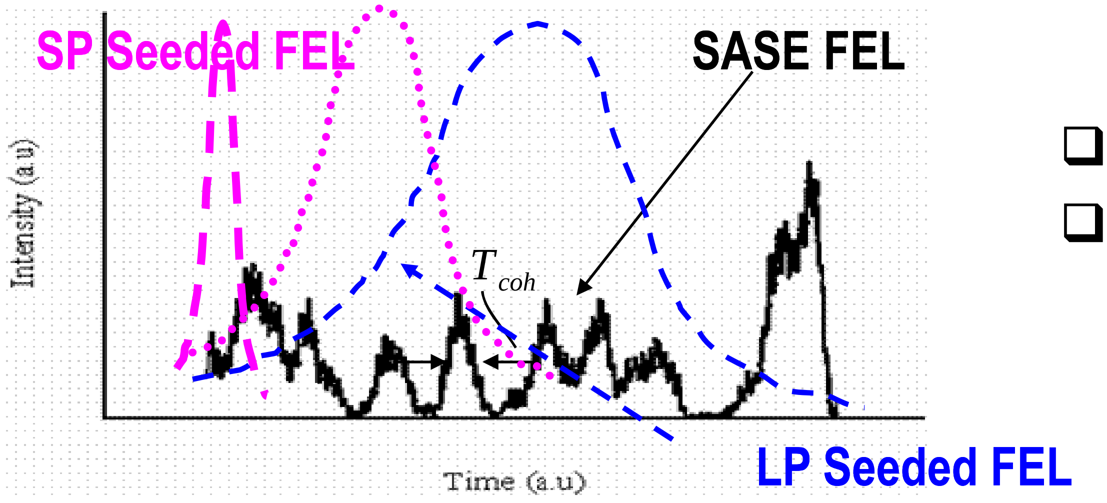
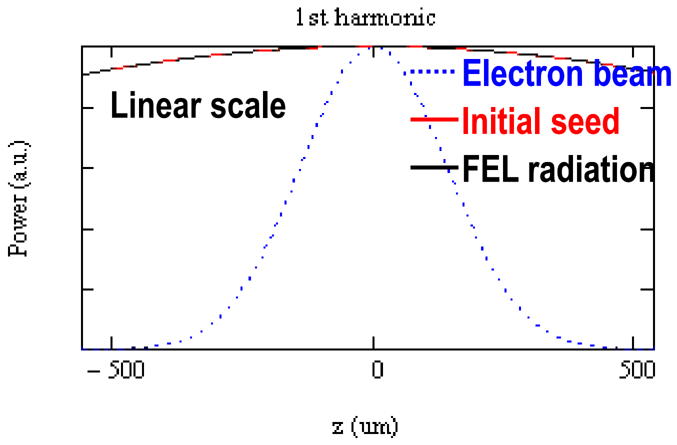
Why Slippage-dominant Superradiant FELs?

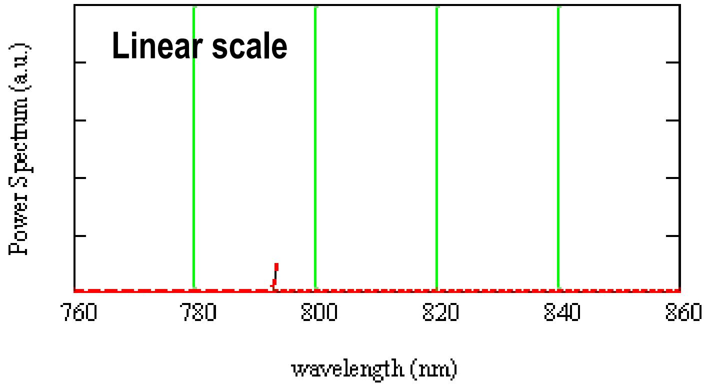


- Large Statistic fluctuations
- Poor temporal coherence

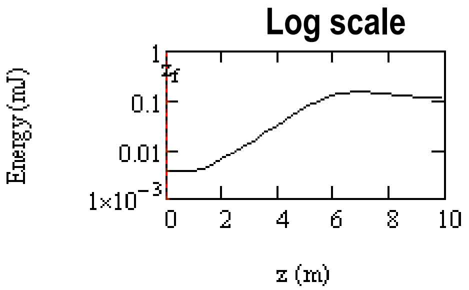
- Many applications requiring improved temporal coherence
- Certain applications preferring spectral tunability
- Seeding with external laser pulse:
  - steady-state regime (long pulse (LP))
  - slippage-dominant superradiant regime (short pulse (SP))
- Both LP and SP have
  - Fully coherent FEL pulse
  - Well-defined timing
  - Less undulators to reach saturation
- Except
  - LP has no spectral tunability || SP has spectral tunability within seed bandwidth

Long pulse seeded FEL



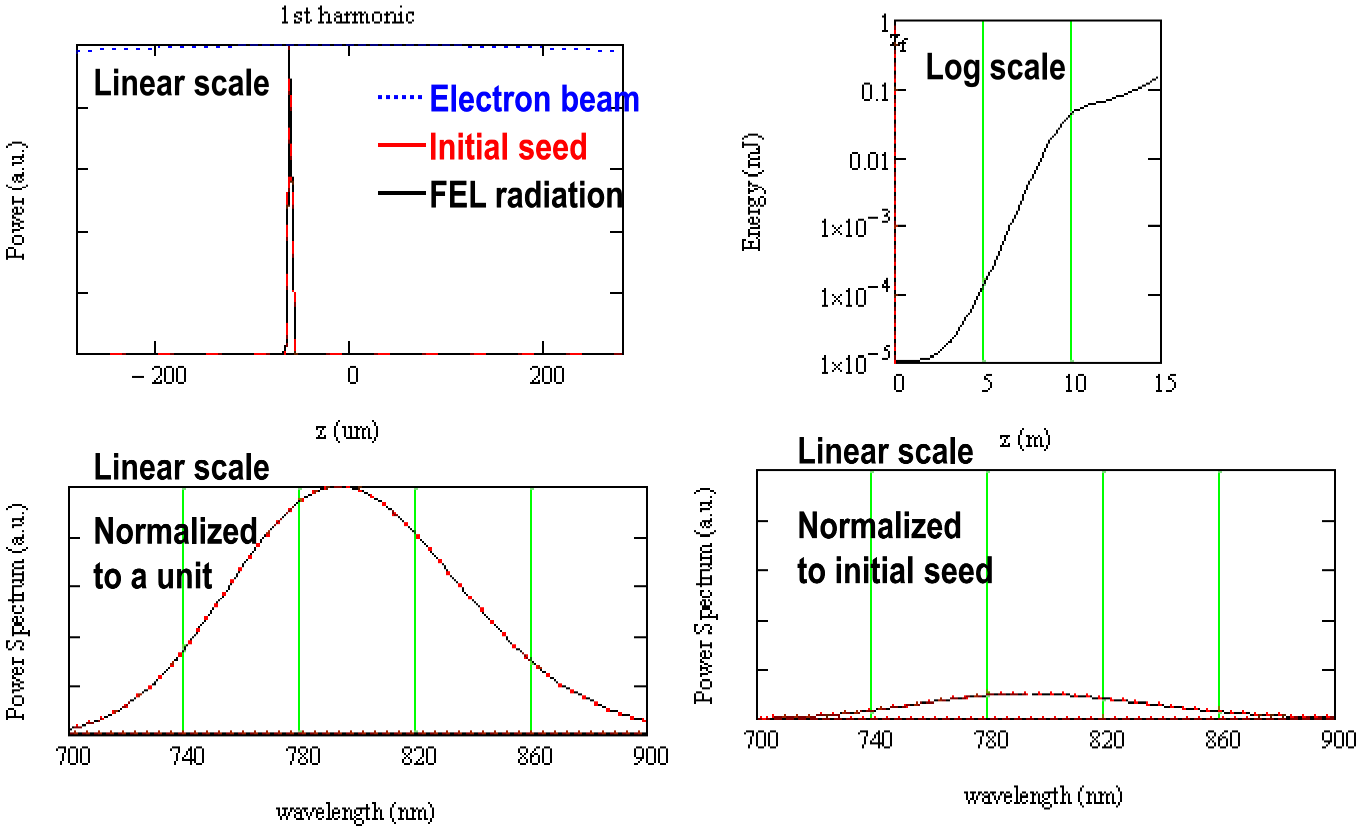


N_r=256
λ_u=3.89cm
P_{seed}=1MW
σ_{e-}=0.47ps
σ_{seed}=6ps
δ_E=0.4%
$\delta_E = \delta \cdot \rho$
$\rho = 3.1 \cdot 10^{-3}$



- Steady state — external seed covering entire e- bunch $L_{SEED} >> L_{e-}$
- External seed initiating FEL process
- Coherent radiation at λ_{seed} amplified to saturation in a radiator
- No spectral tunability

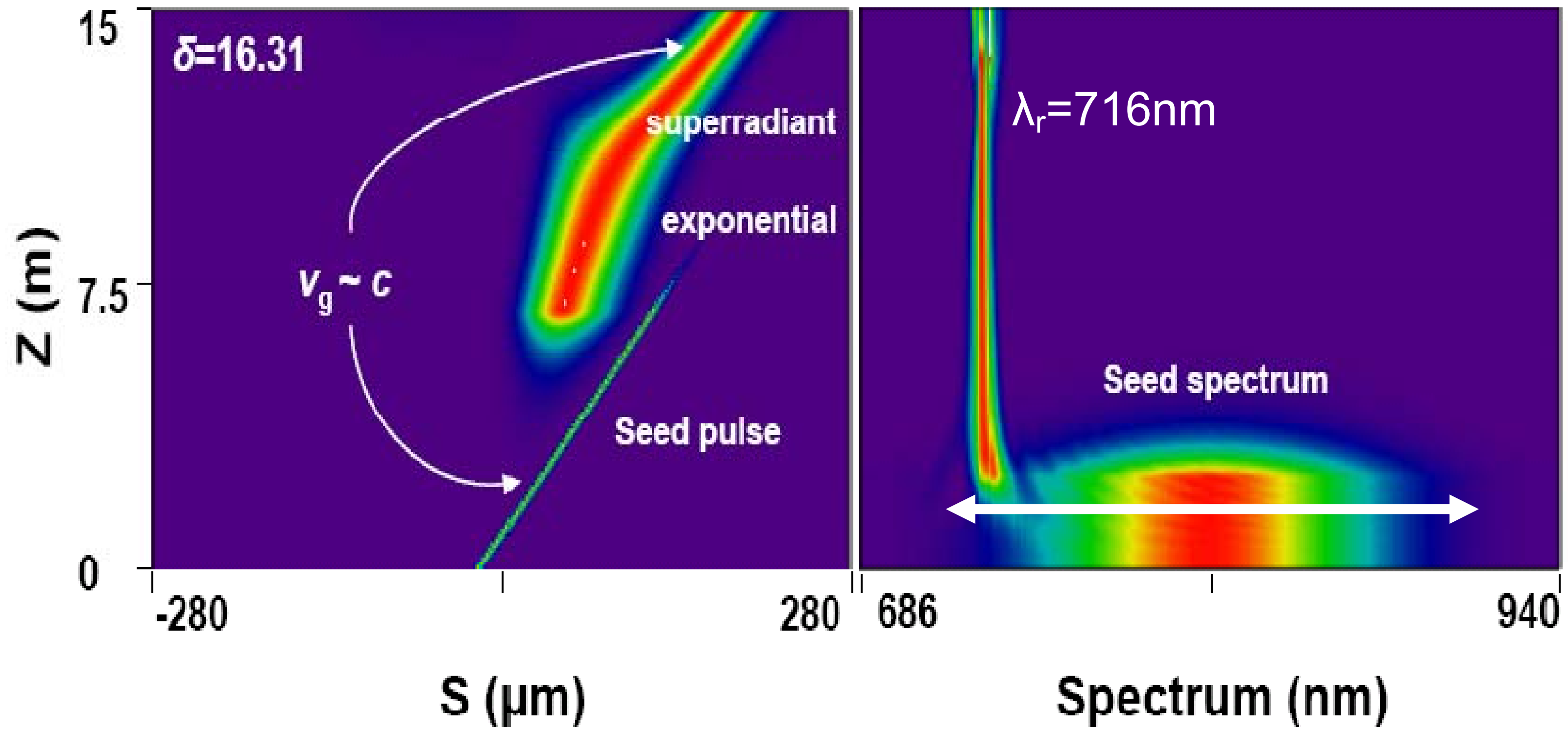
Slippage-dominant Superradiance FEL amplifier



N_r=256
λ_u=3.89cm
P_{seed}=1MW
σ_{e-}=4.7ps
σ_{seed}=6fs
δ_E=3%
$\delta_E = \delta \cdot \rho$
$\rho = 3.1 \cdot 10^{-3}$

- ☐ Slippage-dominant superradiance (SDSP) — $L_{SEED} \approx L_c$ $(=\lambda_r/4\pi\rho) << L_{e-}$; $L_{SEED} << L_s$ $(=\lambda_r N_r)$.
- ☐ External seed, provided by spectral overlap between $\Delta\lambda_{SEED}$ and $\Delta\lambda_r$, coherently bunching electrons in the slippage regime
- ☐ Coherent radiation at SASE λ_r.

Promises



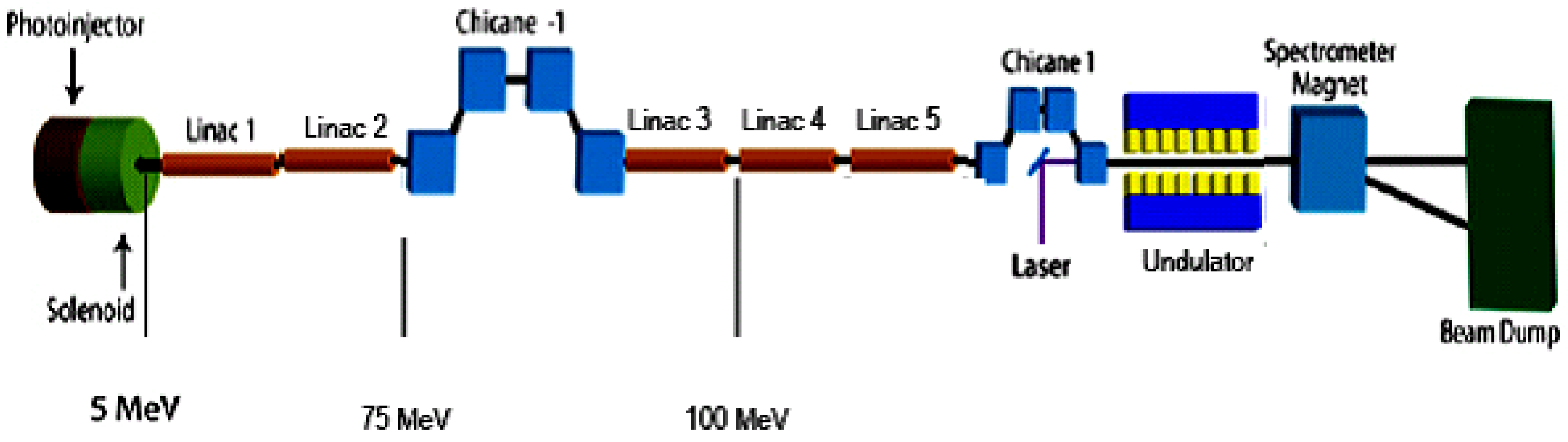
$N_r=256$
$\lambda_u=3.89\text{cm}$
$P_{seed}=1\text{MW}$
$\sigma_{e-}=4.7\text{ps}$
$\sigma_{seed}=6\text{fs}$
$\delta_E=5\%$
$\delta_E=\delta\cdot\rho$
$\rho=3.1\cdot10^{-3}$

- In **SDSR** regime, seed pulse moving at $v_g \approx c$
- Spectral tunability limited by $\Delta\lambda_{SEED}$. As an example,
  - $P_{seed}=1\text{MW}$, 14 fs, $\Delta\lambda_{SEED}=75\text{nm}$, coherent radiation λ_r in the range 678 to 909nm, $\delta_E=\pm7.3\%$.
- Experiment in SDL— $P_{seed}=1\text{-}10\text{MW}$, seed pulse 140 fs, $\Delta\lambda_{SEED}=7.5\text{nm}$, $\lambda_{SEED}=793.5\text{nm}$, tuning range 778 to 809nm, $\delta_E=\pm1\%$.

SDSR FEL: Promises and limitations

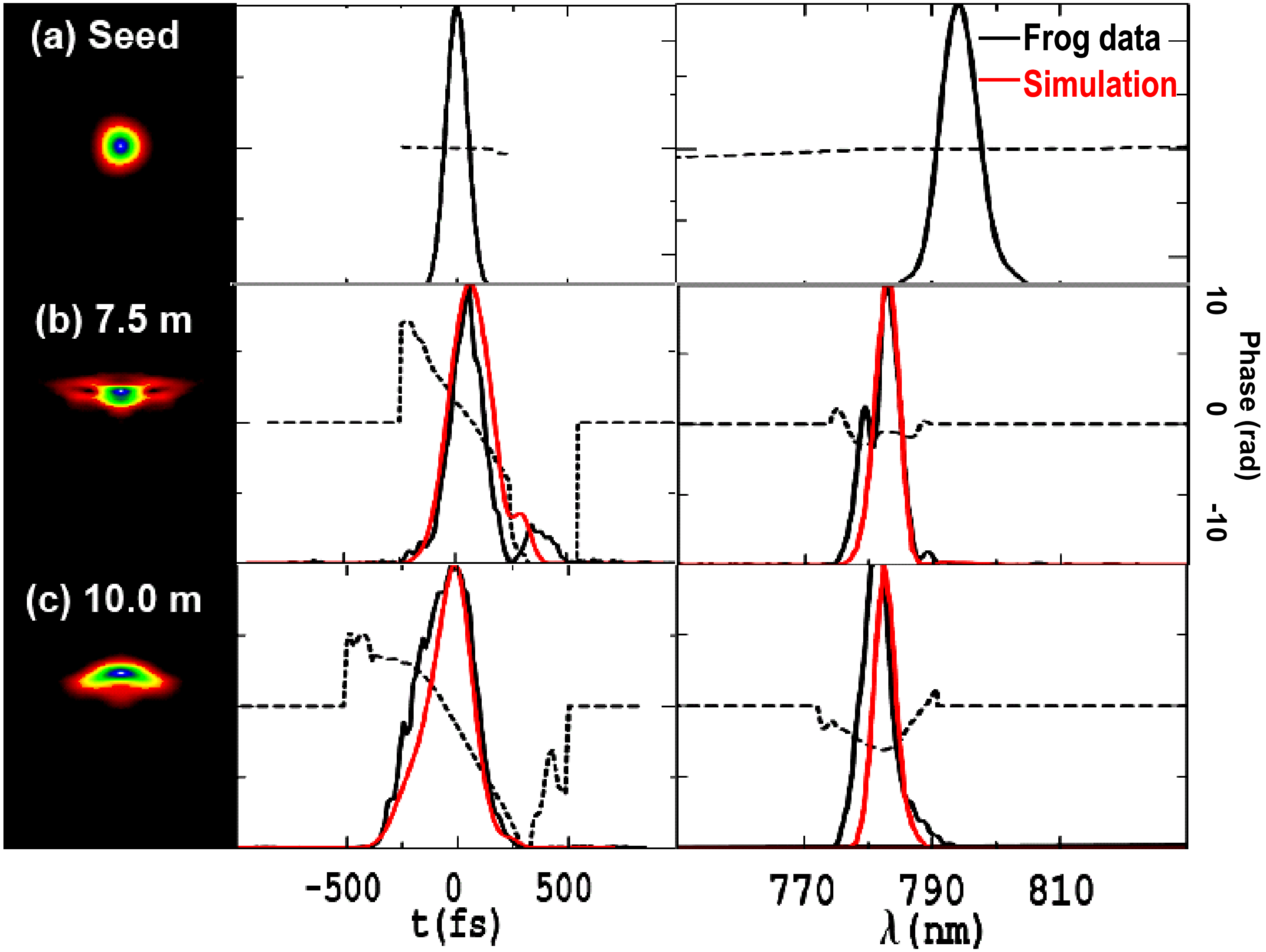
- ☐ **Promises**
  - ➢ Bunching AND Gain
  - ➢ Varying E_{e-} -> Tunable λ_r
  - ➢ Transverse and longitudinal coherences
- ☐ **Limitations**
  - ➢ Spectral tuning range limited by $\Delta\lambda_{SEED}$ ($\gg \Delta\lambda_r$)
  - ➢ FEL efficiency scaled by the slippage in a radiator
  - ➢ Less effective in short λ_r regime

SDSR FEL experiment at NSLS SDL



- ❑ **To-do-list**
  - ➢ Compress e- bunch down to ~1ps (FWHM), at E≈101.75MeV, I_{peak}≈300A, ε ≈4.5μm
  - ➢ Compress seed pulse to Fourier transform limited 140fs (FWHM)
  - ➢ Overlap e- beam and seed laser transversely in the radiator
  - ➢ Scan delay stage to adjust laser timing until the seed enhanced FEL output is observed
  - ➢ FROG, Joule meter, Spectrometer
- ❑ **What to measure?**
  - ➢ The evolution of longitudinal phase space using FROG
  - ➢ Output spectrum versus e- beam energy
  - ➢ Pulse energy versus e- beam energy

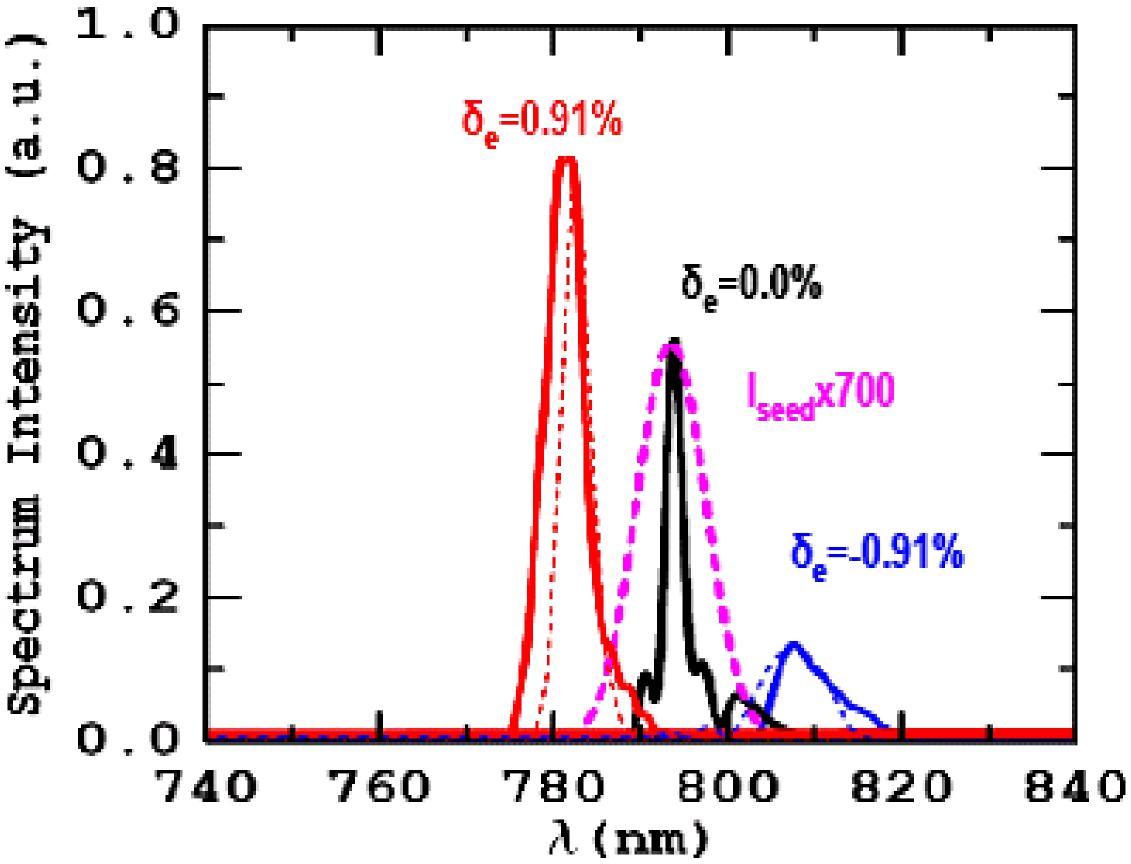
FROG data in good agreement with simulation



δ_e=0.91%, E_{SEED}=0.1μJ

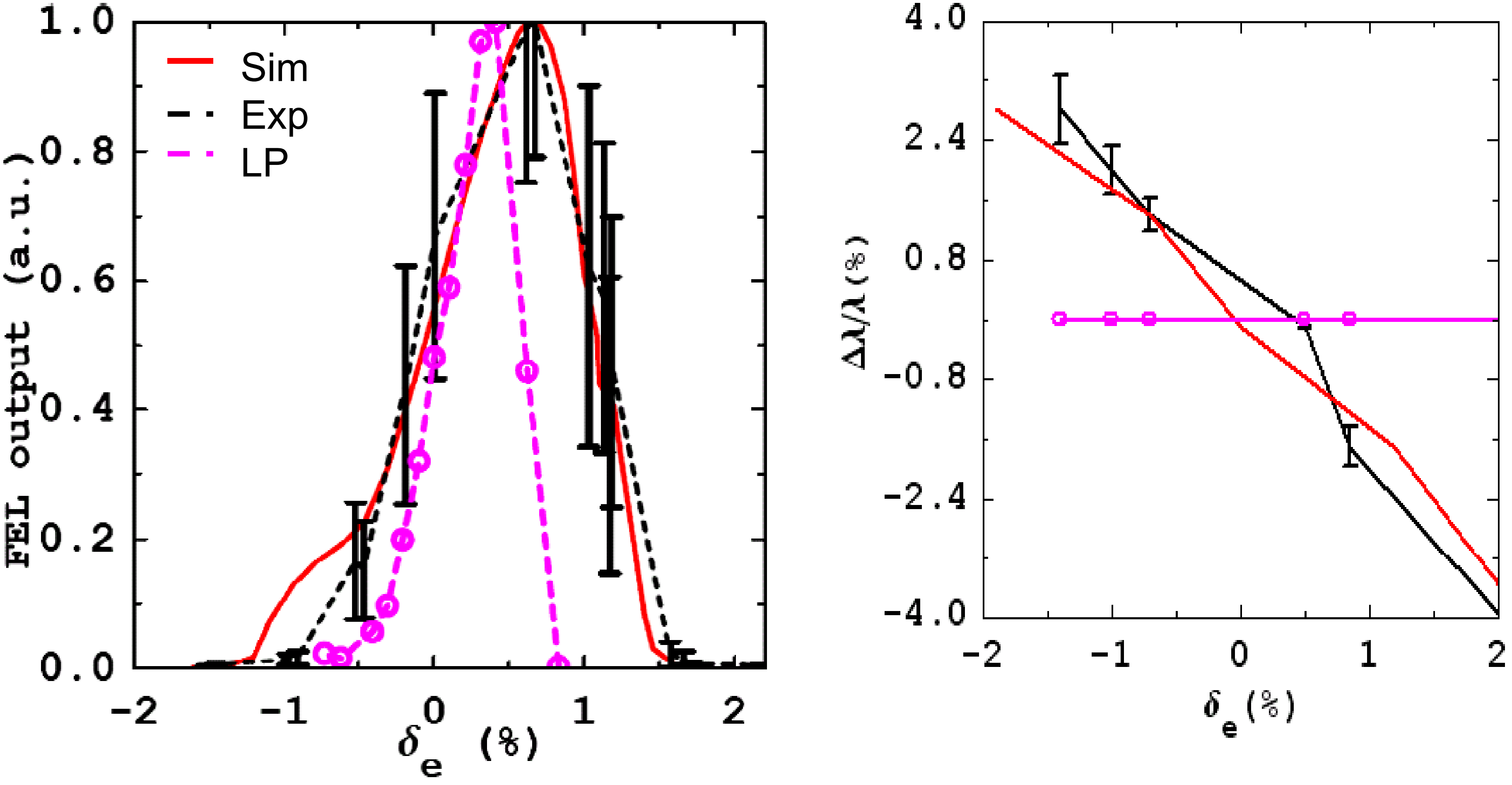
Spectral signal

δ_e=0.91%, E_{SEED}=0.1μJ



Variation of FEL output with beam energy

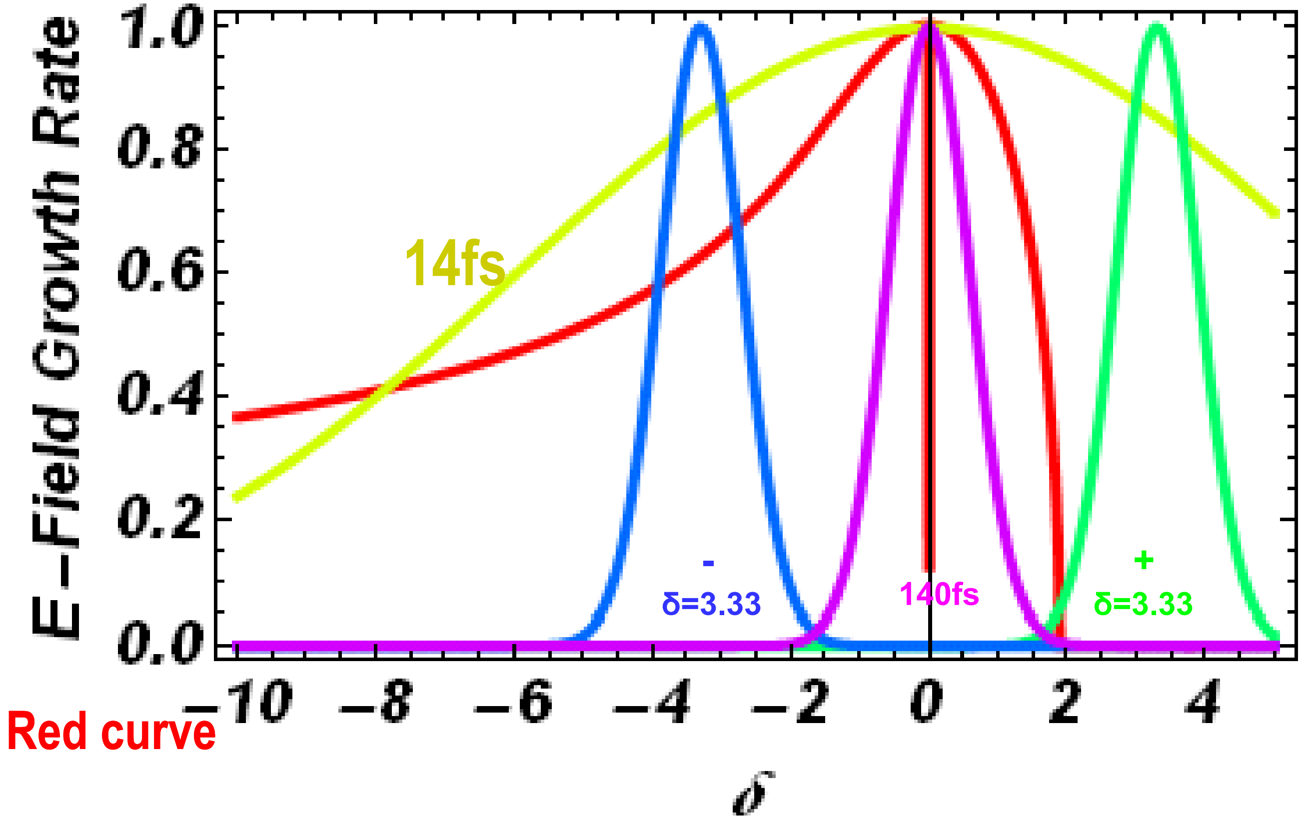
δ_e=0.91%
E_{SEED}=0.1μJ



Summary

- Slippage-dominant superradiance FEL verified
  - Longitudinal coherence observed
  - Spectral tunability within seed bandwidth verified
  - All the experimental observations well explained with slippage superradiance theory
- Ongoing work and future plan:
  - Analytical calculation of bunching factor in broadband seed case confirmed by Perseo simulation --- collaborate with *Luca Giannessi*
  - Exploring short wavelength limit

FEL 1-D theory explanation



$\delta = \delta_E/\rho$

$\rho = 3 \cdot 10^{-3}$