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Trieste

Generation of Intense XVUV Pulses with an Optical Klystron Enhanced SASE FEL

Giuseppe Penco, Enrico Allaria, Giovanni De Ninno, Eugenio Ferrari, Luca Giannessi

FEL 2014 Basel

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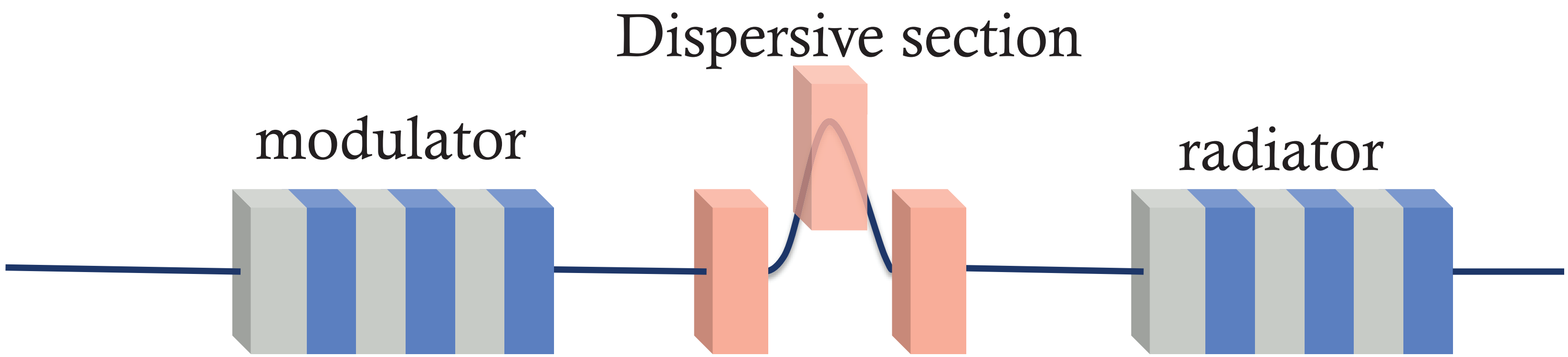
Outline

- Introduction to the optical klystron concept
- Application to high gain FEL: 1-D theory
- Experimental demonstration on FEL-1 at FERMI
    - Study of the Opt. Kly performance vs beam slice energy spread
    - Optical Klystron FEL Gain Curve
- Experiment on FEL-2 at 12 nm
- Conclusion

Optical klystron main concept



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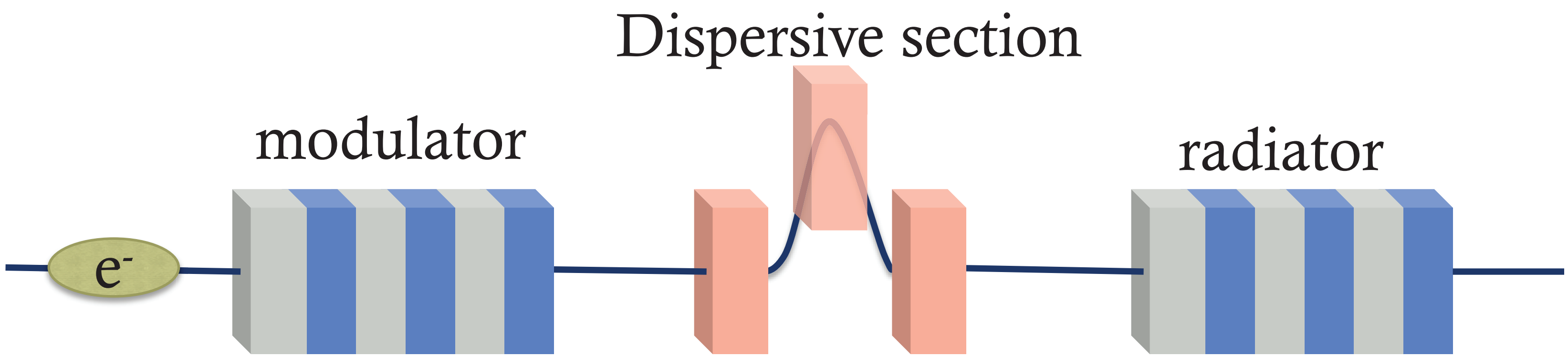
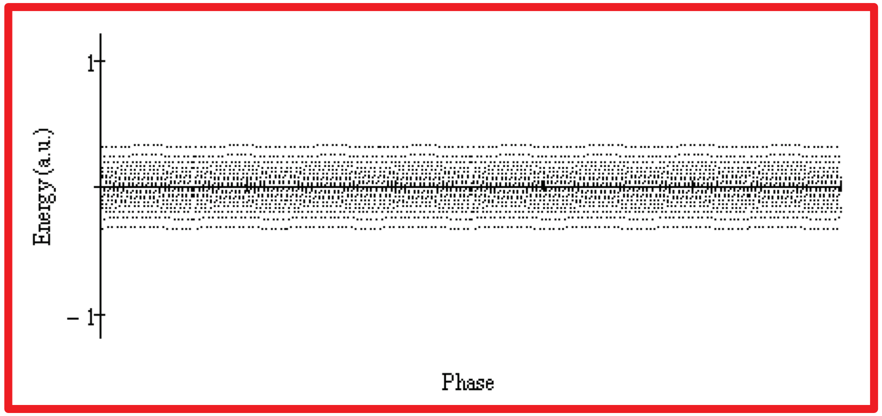
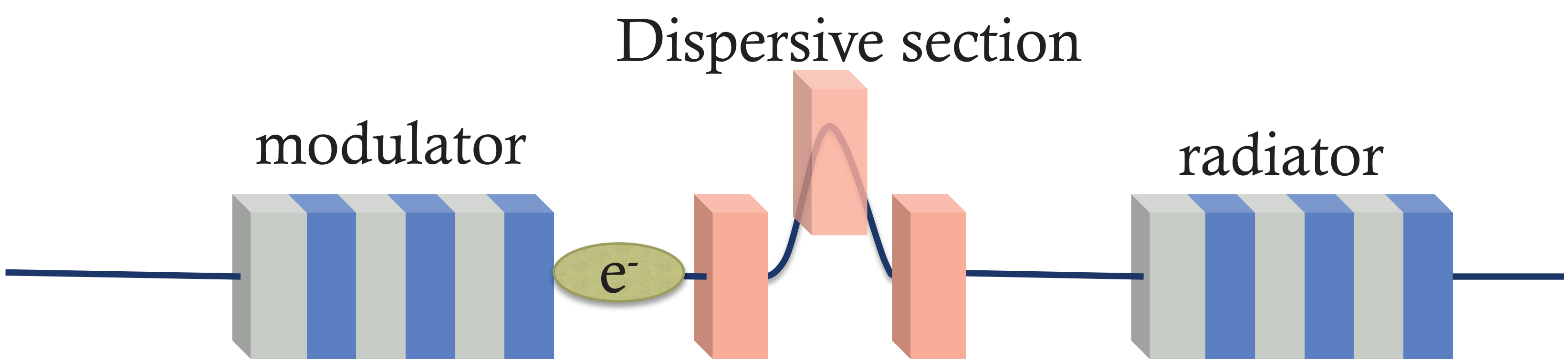
Optical klystron main concept

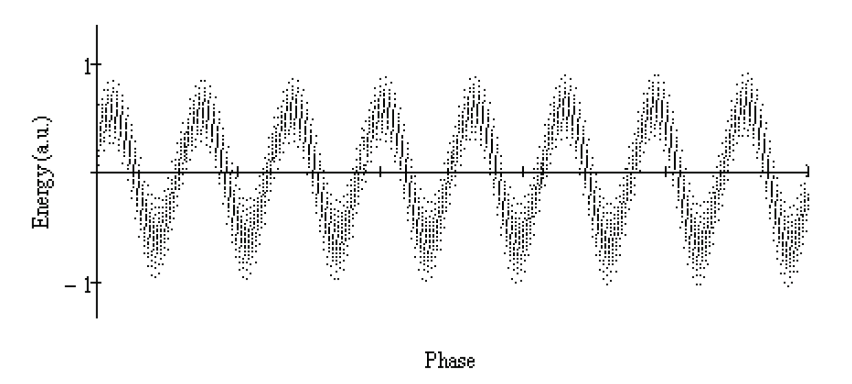




Fresh beam

Optical klystron main concept





Modulated beam

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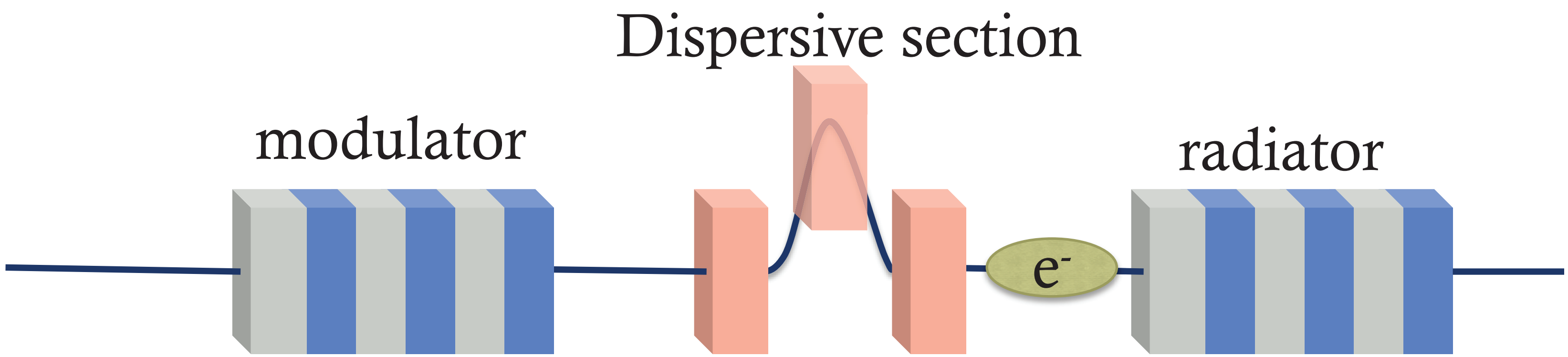
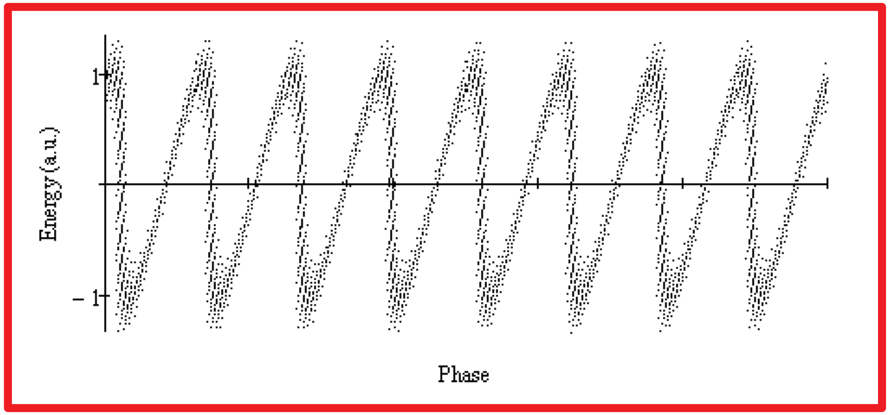
Optical klystron main concept





Bunched beam

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Optical Klystron progress: from low-gain to high-gain FEL

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- First proposal of implementing an optical klystron (OK) to a Storage Ring FEL:
  - Vinokurov and Skrinsky, *Preprint of INP 77-59, Novosibirsk, **(1977)***
  - Artamonov et al., (1st exp. on VEPP-3 SR): *NIM-A **177**, 247-252 **(1980)***
- Opt. klystron FELs on Storage Rings (Oscillator facility):
  - ACO storage ring (lasing at 635nm) : *Phys Rev. Lett. 51, 1652 **(1983)***
  - SUPER-ACO storage ring (490nm): *Rev. Sci. Instrum. 60, 1429 **(1989)***
  - OK-4/VEPP-3 storage ring (240nm): *NIM-A 282, 424-430 **(1989)***
  - OK-4/Duke SR FEL lased at 193.7-209nm in **1999** (*NIM-A 475, 195 (2001)*)
  - ELETTRA SR FEL lased at 217.9nm in **2000** (*NIM-A 475, 20 (2001), PRL 100, 104801 (2008)*)
  - Distributed-OK SRFEL (Duke) improved the gain in **2006** (*Phys. Rev. Lett. 96, 224801*).

- A number of theoretical studies of OK in high-gain FEL amplifier, as (not exhaustive list):
  - *Bonifacio et al. Phys. Rev. A 45, 4091 (1992);*
  - *Dattoli et al., NIM-A 333, 589 (1993);*
  - *Vinokurov et al. NIM-A 375, 264 (1996);*
  - *S.J. Hahn and K.H. Pae, Journal of the Korean Phys. Soc. 31, 856 (1997)*
  - *Kim, NIM-A 407, 126 (1998);*
  - *Neil and Freund, NIM-A 475, 381 (2001);*
  - *Saldin et al., DESY 03-108 (2003)*
  - *Ding et al, Phys. Rev. ST-AB 9, 070702 (2006)*
  - *….*

Short Review of 1-D theory for OK SASE

- K. J. Kim, NIM-A **407**, 126 (1998)
- Y. Ding et al., Phys Rev ST-AB **9**, 070702 (2006)

Enhancement factor to the rad. field Eν

$$R(\nu) \equiv \frac{E_\nu^{\mathrm{OK}}}{E_\nu^{\mathrm{no\ OK}}} = \frac{1 - \int d\xi \frac{dV(\xi)/d\xi}{(\mu-\xi)^2} e^{-i\rho k_r \nu R_{56}\xi} e^{ik_r\nu R_{56}/2}}{1 + 2\int d\xi \frac{V(\xi)}{(\mu-\xi)^3}}$$

$\nu = \omega/\omega_r$
ρ=Pierce parameter
$\xi = \delta/\rho$
$\delta = (\gamma - \gamma_0)/\gamma_0$
$V(\xi)$ en distr. of e-beam

Where $\mu = (-1 + i\sqrt{3})/2$ is the complex growth rate of Eν in each undulator (for a beam with a vanishing en. spread)

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Enhancement factor to the rad. field Eν

Radiation in the 1st und.

μbunching induced by the chicane

$$R(\nu) \equiv \frac{E_\nu^{\mathrm{OK}}}{E_\nu^{\mathrm{no\ OK}}} = \frac{1 - \int d\xi \frac{dV(\xi)/d\xi}{(\mu-\xi)^2} e^{-i\rho k_r \nu R_{56}\xi} e^{ik_r\nu R_{56}/2}}{1 + 2\int d\xi \frac{V(\xi)}{(\mu-\xi)^3}}$$

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Enhancement factor to the rad. field Eν

Radiation in the 1st und. (green box): $\frac{dV(\xi)/d\xi}{(\mu-\xi)^2}$

μbunching induced by the chicane (red box): $e^{-i\rho k_r \nu R_{56}\xi}$

Electron phase slippage (blue box): $e^{ik_r \nu R_{56}/2}$

$$R(\nu) \equiv \frac{E_\nu^{\mathrm{OK}}}{E_\nu^{\mathrm{no\ OK}}} = \frac{1 - \int d\xi \frac{dV(\xi)/d\xi}{(\mu-\xi)^2} e^{-i\rho k_r \nu R_{56}\xi} e^{ik_r \nu R_{56}/2}}{1 + 2\int d\xi \frac{V(\xi)}{(\mu-\xi)^3}}$$

$\nu=\omega/\omega_r$

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$V(\xi)$ en distr. of e-beam

Where $\mu = (-1 + i\sqrt{3})/2$ is the complex growth rate of Eν in each undulator (for a beam with a vanishing en. spread)

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Enhancement factor to the rad. field Eν

Radiation in the 1st und. — μbunching induced by the chicane — Electron phase slippage

$$R(\nu) \equiv \frac{E_\nu^{\text{OK}}}{E_\nu^{\text{no OK}}} = \frac{1 - \int d\xi \frac{dV(\xi)/d\xi}{(\mu-\xi)^2} e^{-i\rho k_r \nu R_{56}\xi} e^{ik_r\nu R_{56}/2}}{1 + 2\int d\xi \frac{V(\xi)}{(\mu-\xi)^3}}$$

- $\nu=\omega/\omega_r$
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- $\xi=\delta/\rho$
- $\delta=(\gamma-\gamma_0)/\gamma_0$
- $V(\xi)$ en distr. of e-beam

Where $\mu = (-1 + i\sqrt{3})/2$ is the complex growth rate of Eν in each undulator (for a beam with a vanishing en. spread)

Using the average SASE spectrum: $S(\nu) = \frac{1}{\sqrt{2\pi}\sigma_\nu} \exp\left[-\frac{(\nu-1)^2}{2\sigma_\nu{}^2}\right]$

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$$G = \int d\nu \left|R(\nu)\right|^2 S(\nu) \approx \frac{1}{9}\left[5 + D^2 e^{-D^2\sigma_\xi^2} + 2\sqrt{3} D e^{-\frac{D^2\sigma_\xi^2}{2}} + \left(\left(4+\sqrt{3}D\right) e^{-\frac{D^2\sigma_\xi^2}{2}} \cos\left(\frac{D}{2\rho}\right) - D e^{-\frac{D^2\sigma_\xi^2}{2}} \sin\left(\frac{D}{2\rho}\right)\right) e^{-\frac{D^2\sigma_\upsilon^2}{8\rho^2}}\right]$$

$$\sigma_\xi = \sigma_\delta/\rho$$

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Enhancement factor to the rad. field E_ν

Radiation in the 1st und. — μbunching induced by the chicane — Electron phase slippage

$$R(\nu) \equiv \frac{E_\nu^{\mathrm{OK}}}{E_\nu^{\mathrm{no\ OK}}} = \frac{1 - \int d\xi \frac{dV(\xi)/d\xi}{(\mu-\xi)^2} e^{-i\rho k_r \nu R_{56}\xi} e^{ik_r\nu R_{56}/2}}{1 + 2\int d\xi \frac{V(\xi)}{(\mu-\xi)^3}}$$

$\nu=\omega/\omega_r$

ρ=Pierce parameter

$\xi=\delta/\rho$

$\delta=(\gamma-\gamma_0)/\gamma_0$

$V(\xi)$ en distr. of e-beam

Where $\mu = (-1 + i\sqrt{3})/2$ is the complex growth rate of E_ν in each undulator (for a beam with a vanishing en. spread)

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when
$D = k_r R_{56}\rho >> 1$

$\sigma_\xi=\sigma_\delta/\rho$

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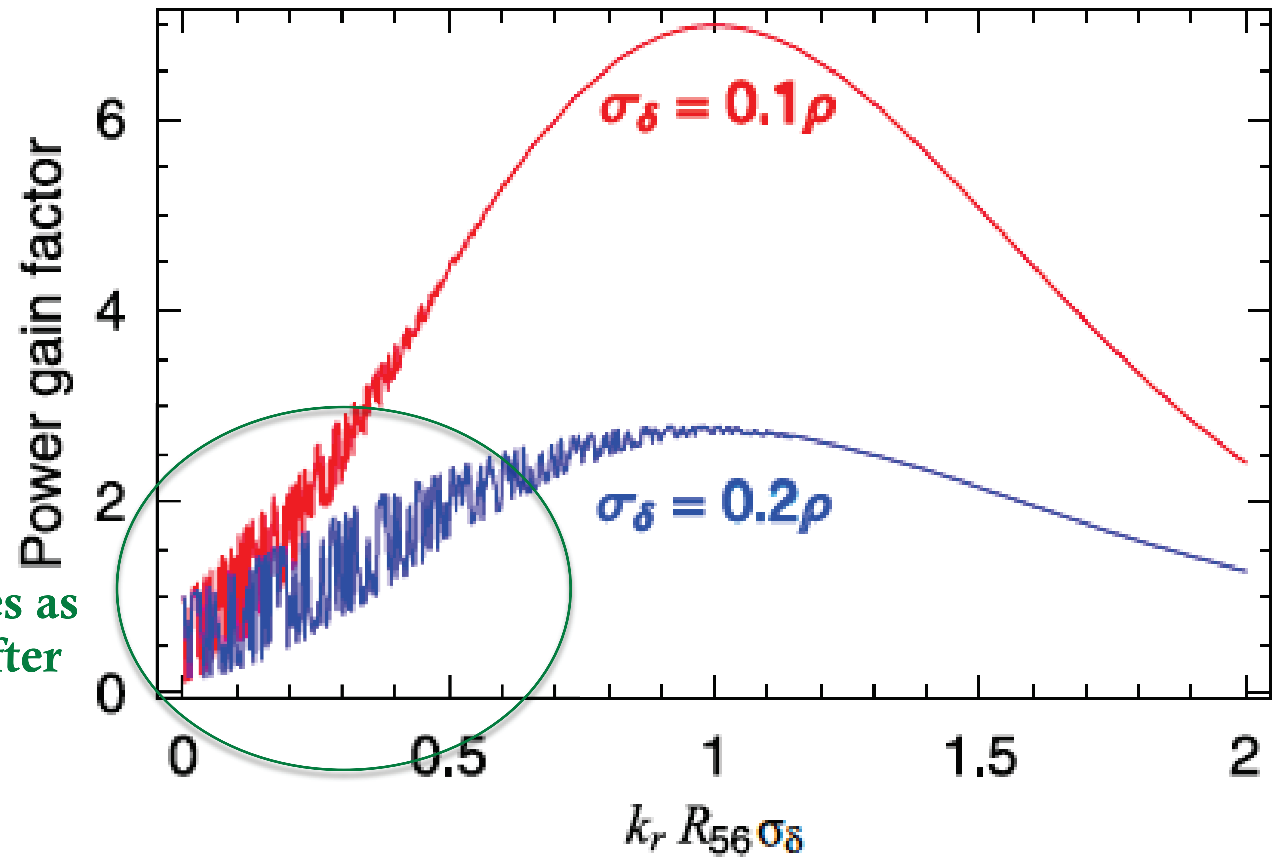
when $D = k_r R_{56} \rho >> 1$

$$G \approx \frac{1}{9}\left[5 + D^2 e^{-D^2\sigma_\xi^2} + 2\sqrt{3} D e^{-\frac{D^2\sigma_\xi^2}{2}}\right]$$

$\sigma_\xi=\sigma_\delta/\rho$

The ratio σ_δ/ρ is a key parameter

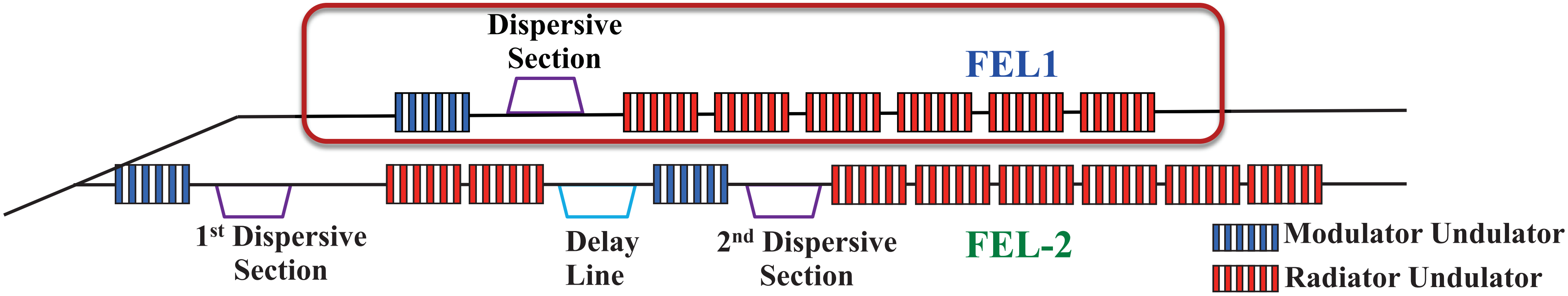


OK operates as a phase shifter

FIG. 1. (Color) 1D power gain factor G with relative energy spread $\sigma_\delta = 0.1\rho$ (red line) and $\sigma_\delta = 0.2\rho$ (blue line).

Y. Ding et al., Phys Rev ST-AB **9**, 070702 (2006)

Experiment at FERMI (FEL-1 line)



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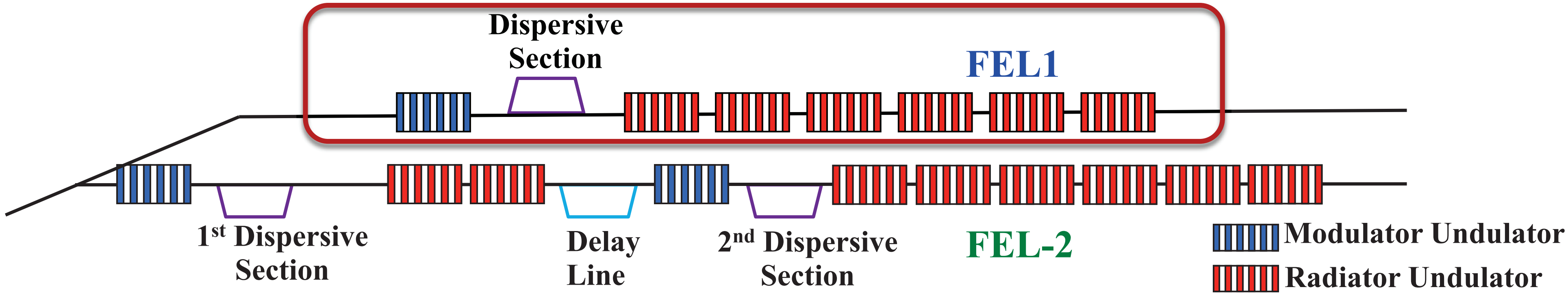

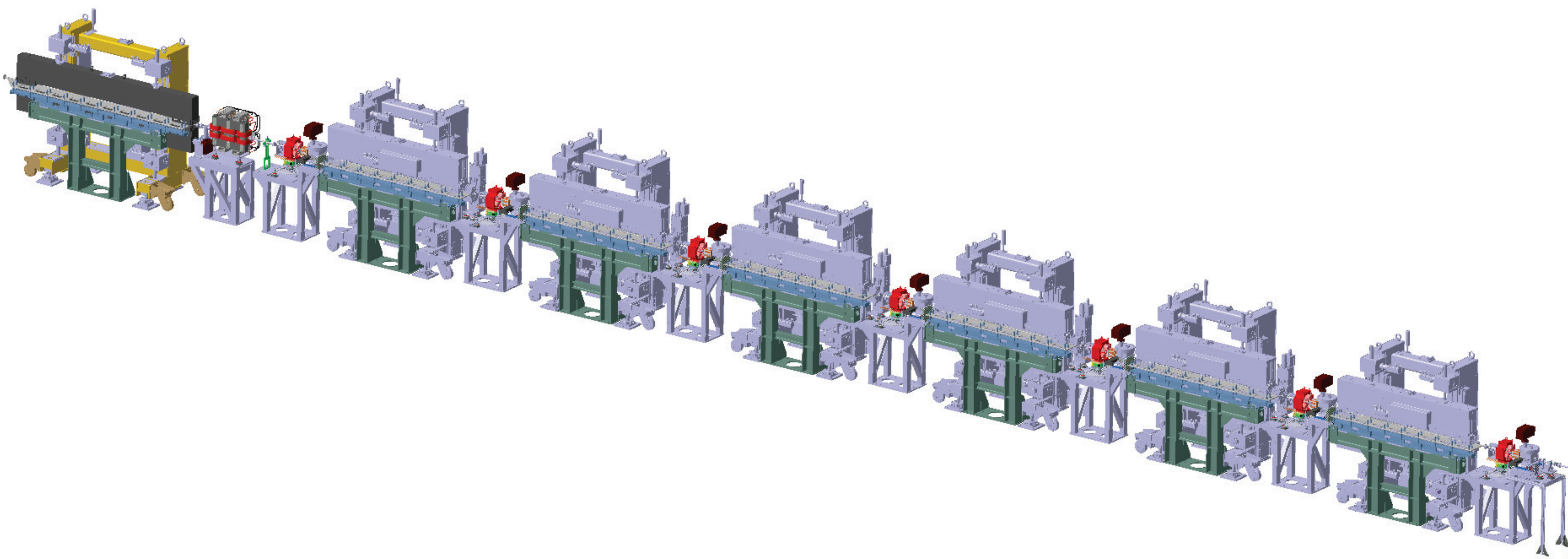

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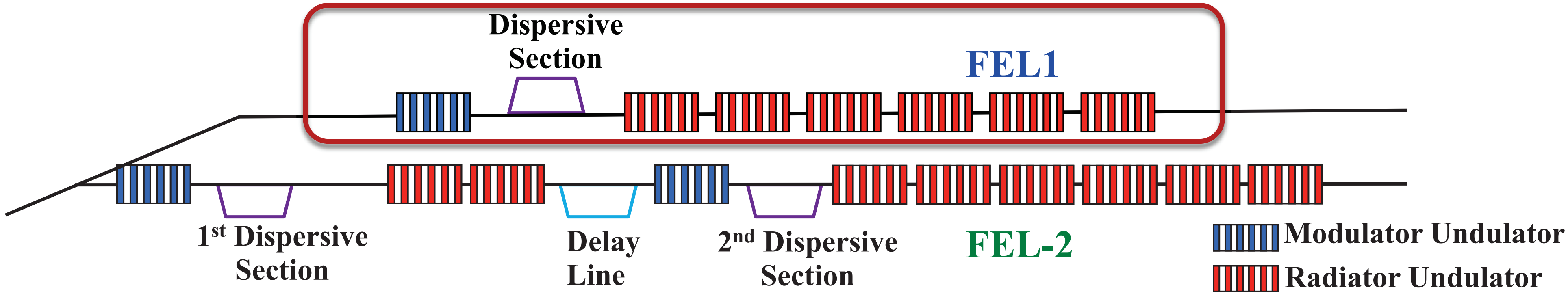

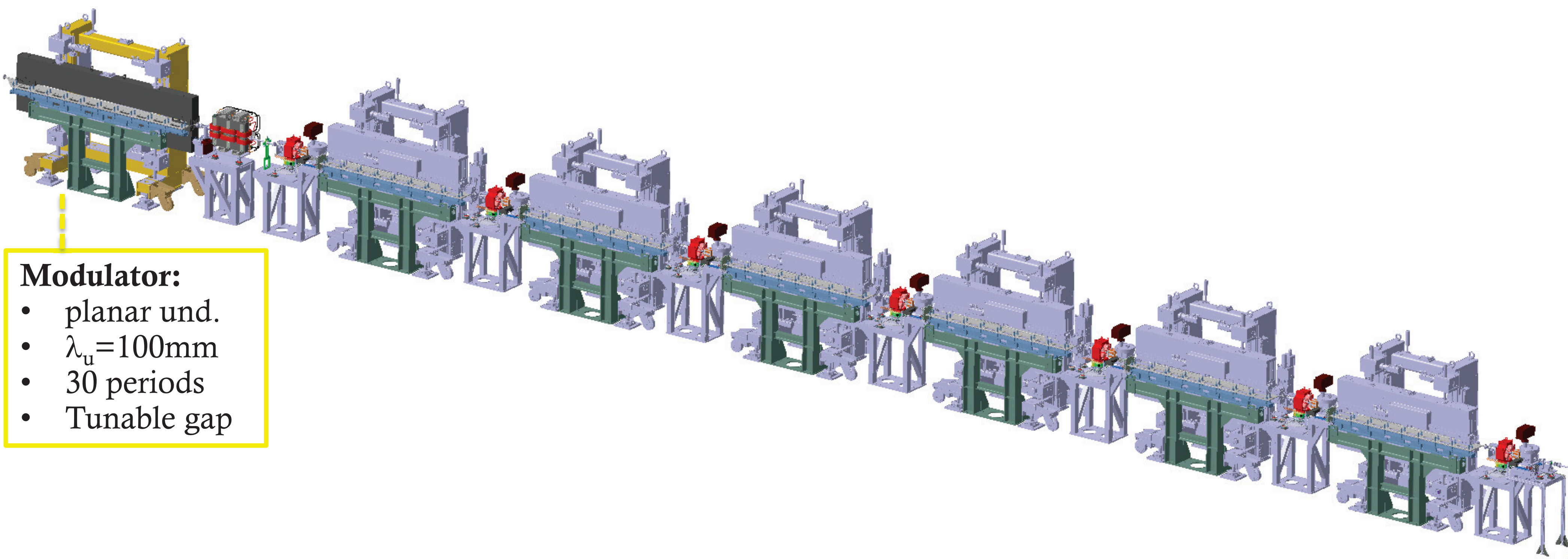

Modulator:
- planar und.
- λ_u=100mm
- 30 periods
- Tunable gap

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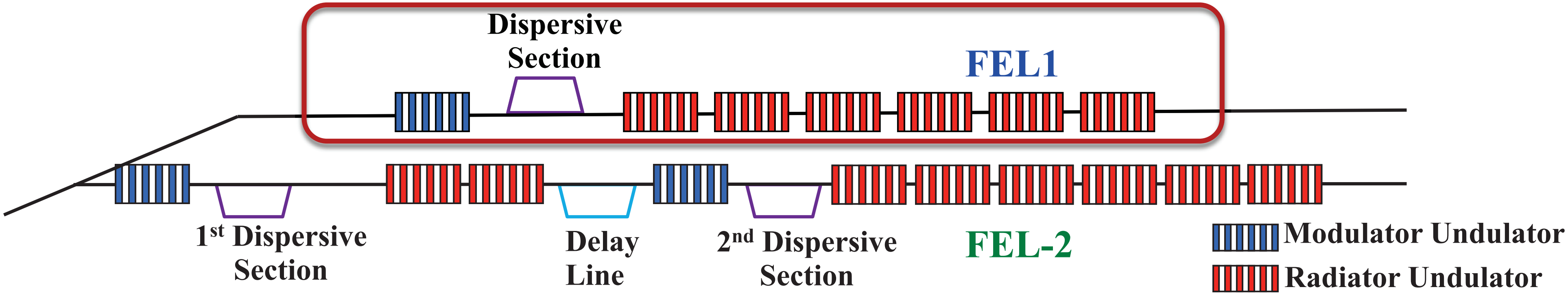
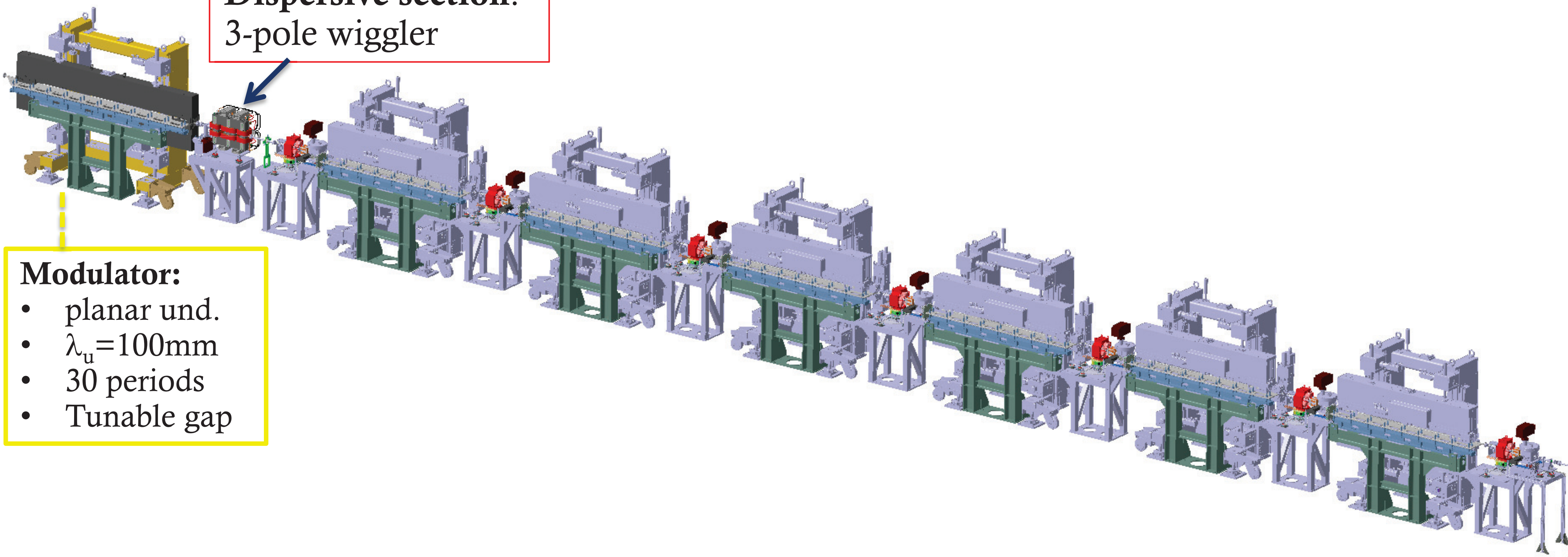
Experiment at FERMI (FEL-1 line)



Dispersive section: 3-pole wiggler



Modulator:
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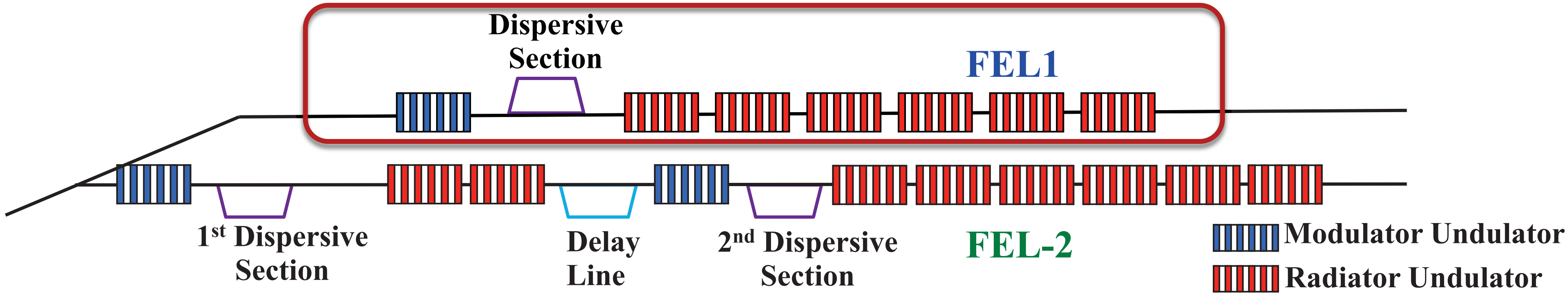
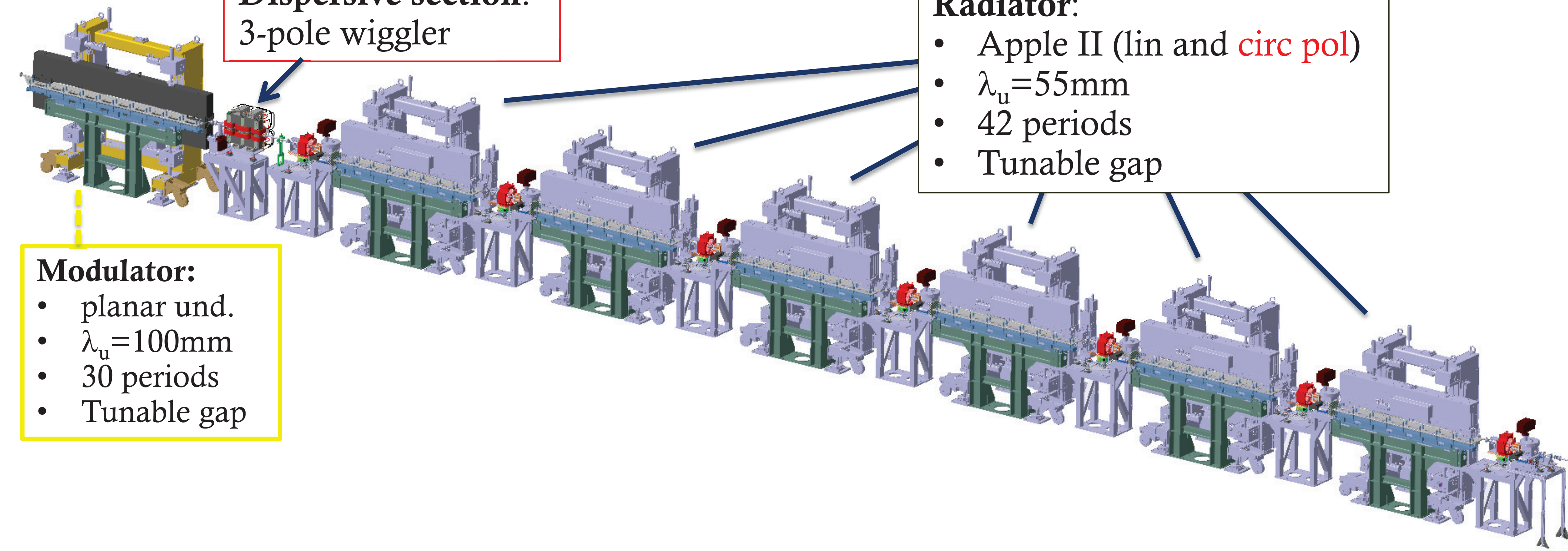
Experiment at FERMI (FEL-1 line)



Dispersive section: 3-pole wiggler

Radiator:
- Apple II (lin and circ pol)
- λ_u=55mm
- 42 periods
- Tunable gap



Modulator:
- planar und.
- λ_u=100mm
- 30 periods
- Tunable gap

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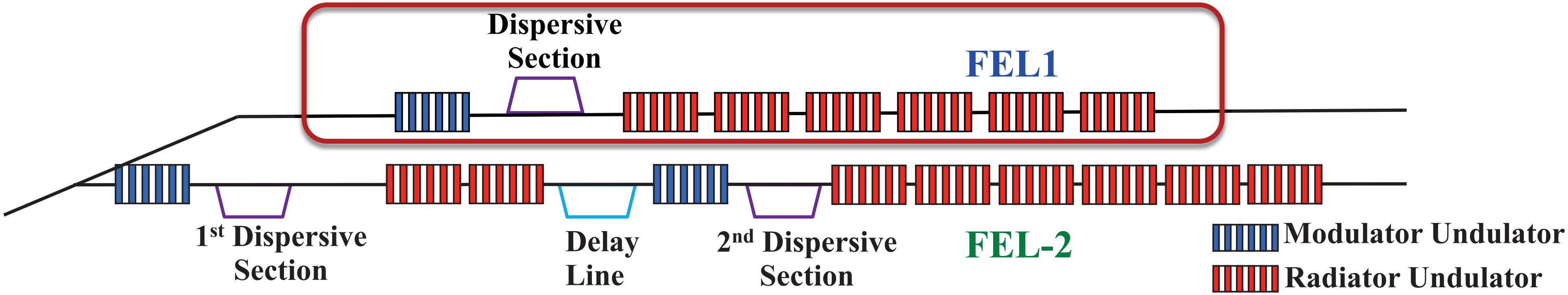
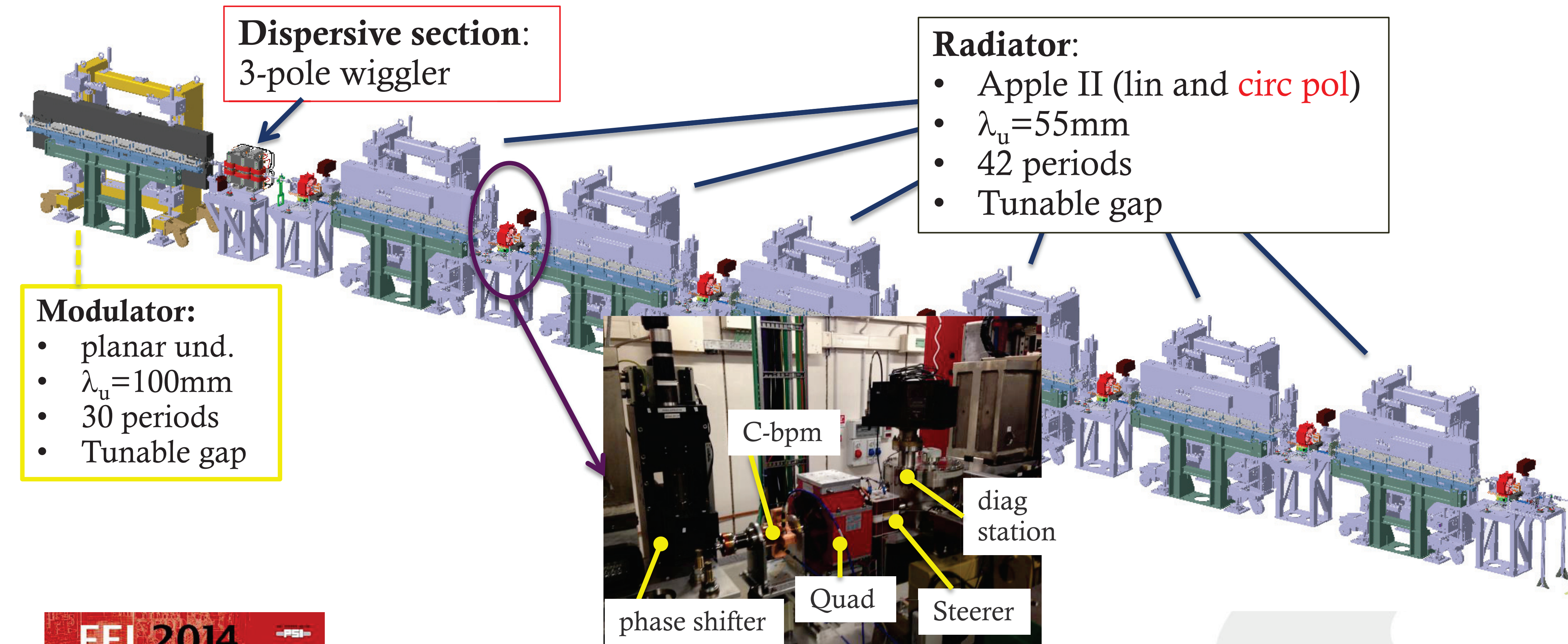
Experiment at FERMI (FEL-1 line)





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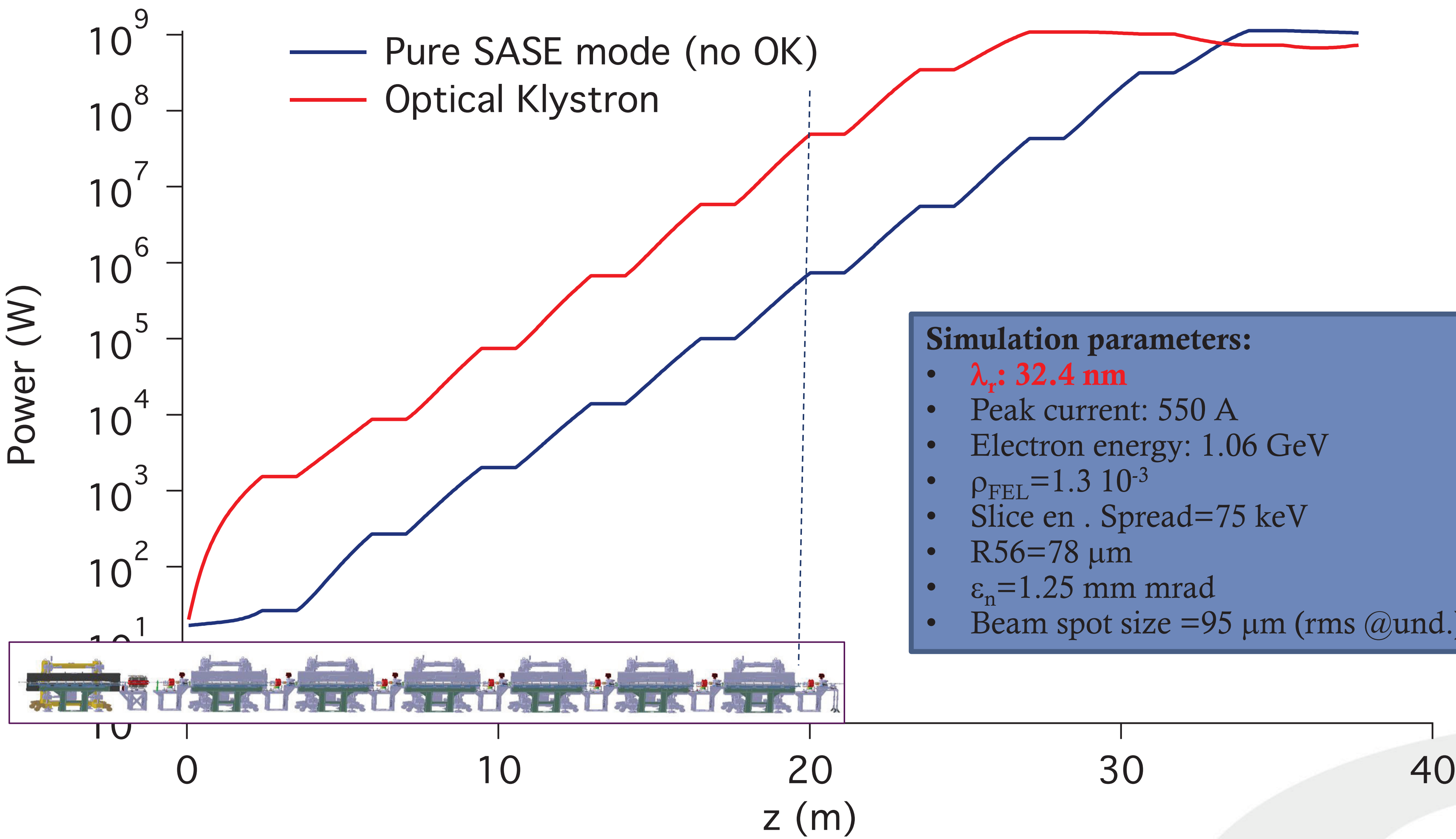
Simulation results (GENESIS)



Simulation parameters:

- **λ_r: 32.4 nm**
- Peak current: 550 A
- Electron energy: 1.06 GeV
- ρ_{FEL}=1.3 10^{-3}
- Slice en . Spread=75 keV
- R56=78 μm
- ε_n=1.25 mm mrad
- Beam spot size =95 μm (rms @und.)

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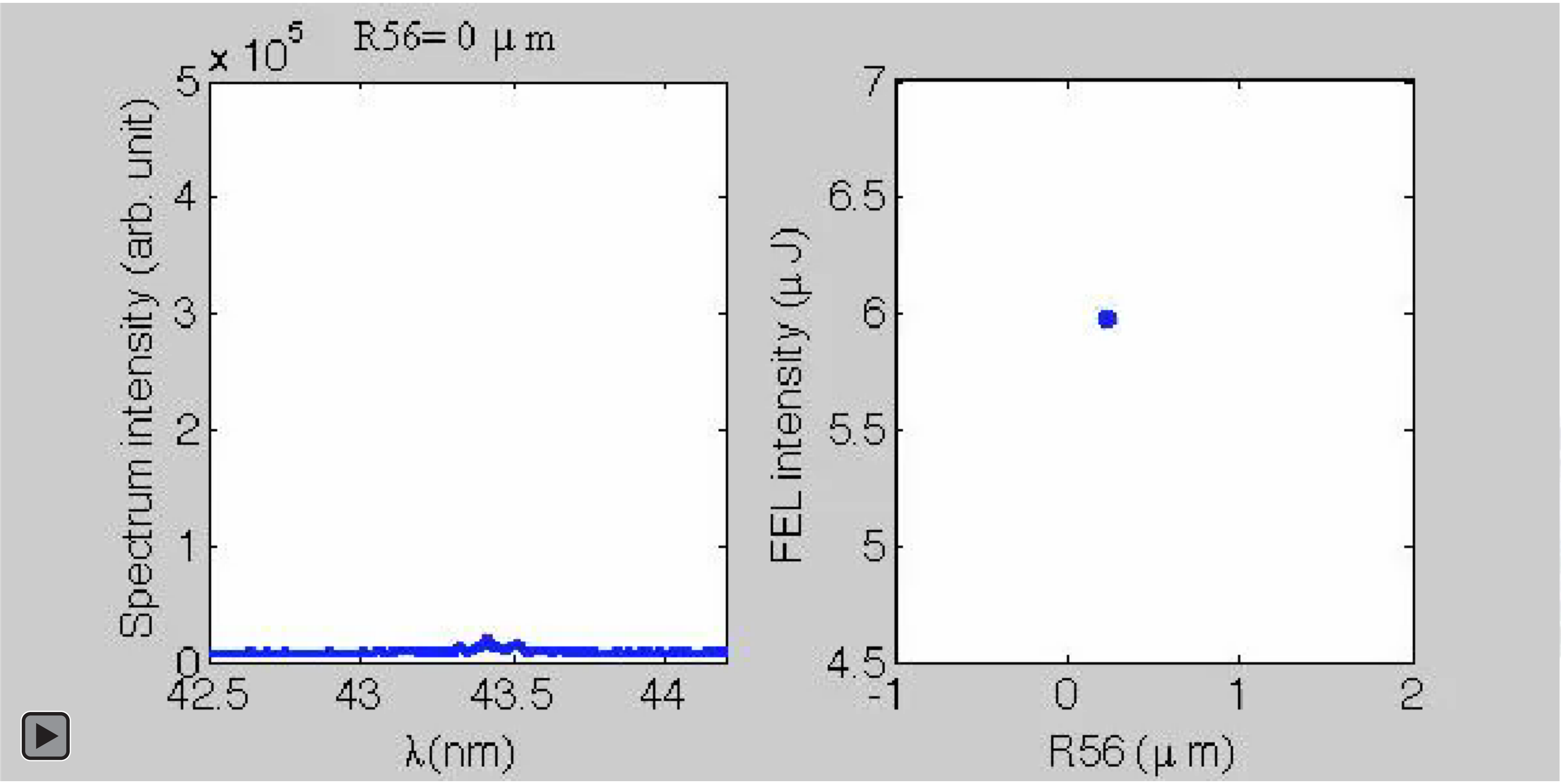
SASE intensity and spectrum vs Dispersive Section R_{56}

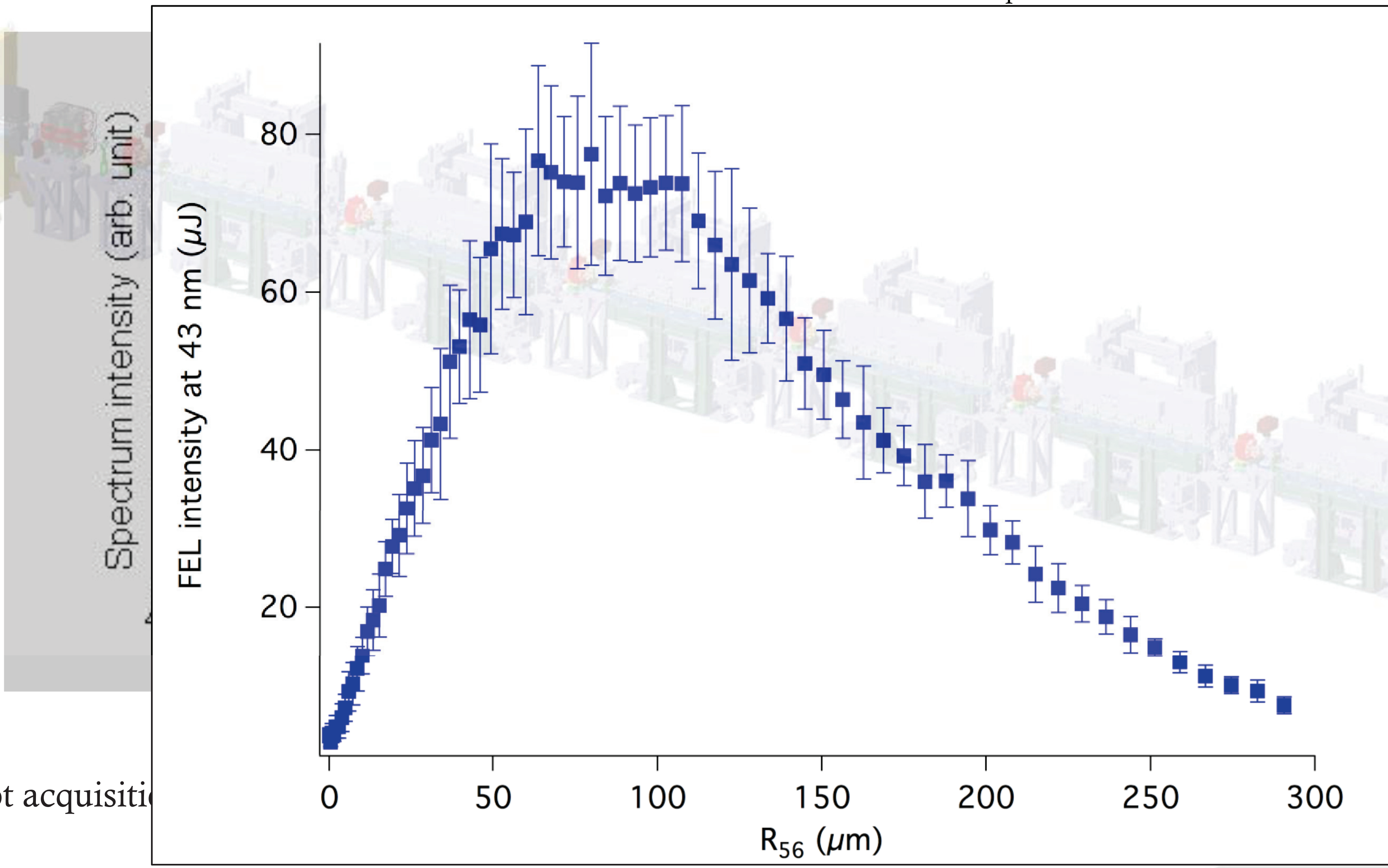
E-beam: Q=500 pC, I_p=500 A, E=1.058 GeV



Shot-to-shot acquisition at 10Hz

SASE intensity and spectrum vs Dispersive Section R_{56}

E-beam: Q=500 pC, I_p=500 A, E=1.058 GeV



Shot-to-shot acquisiti

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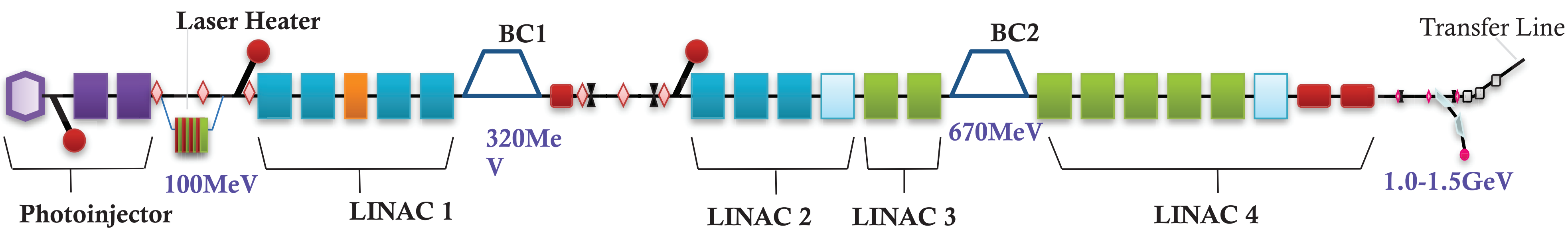
Opt. Kly. performance versus σ_E (1/3)

We can control the beam slice en. spread by using the laser heater



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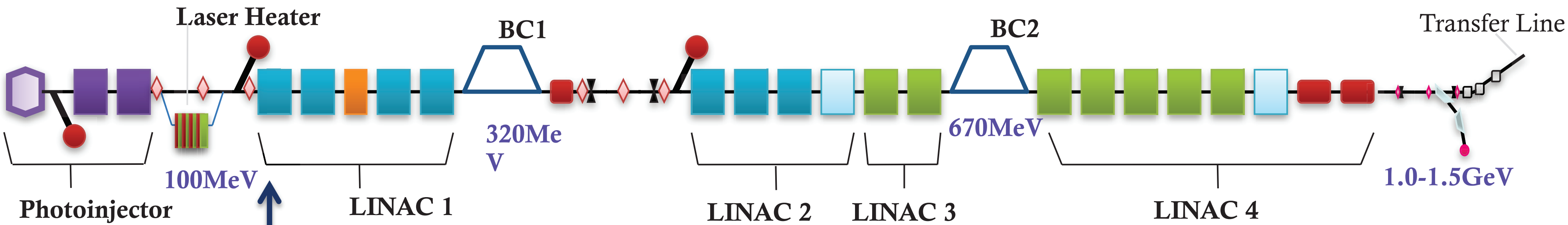

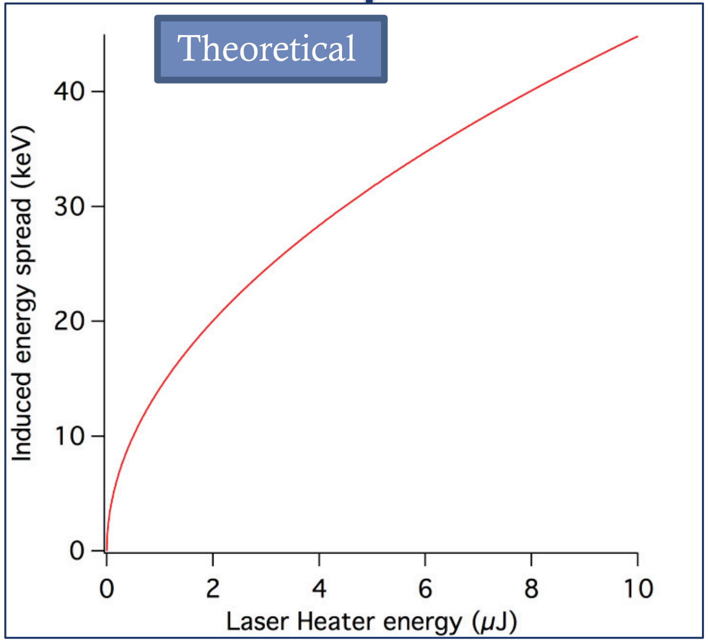

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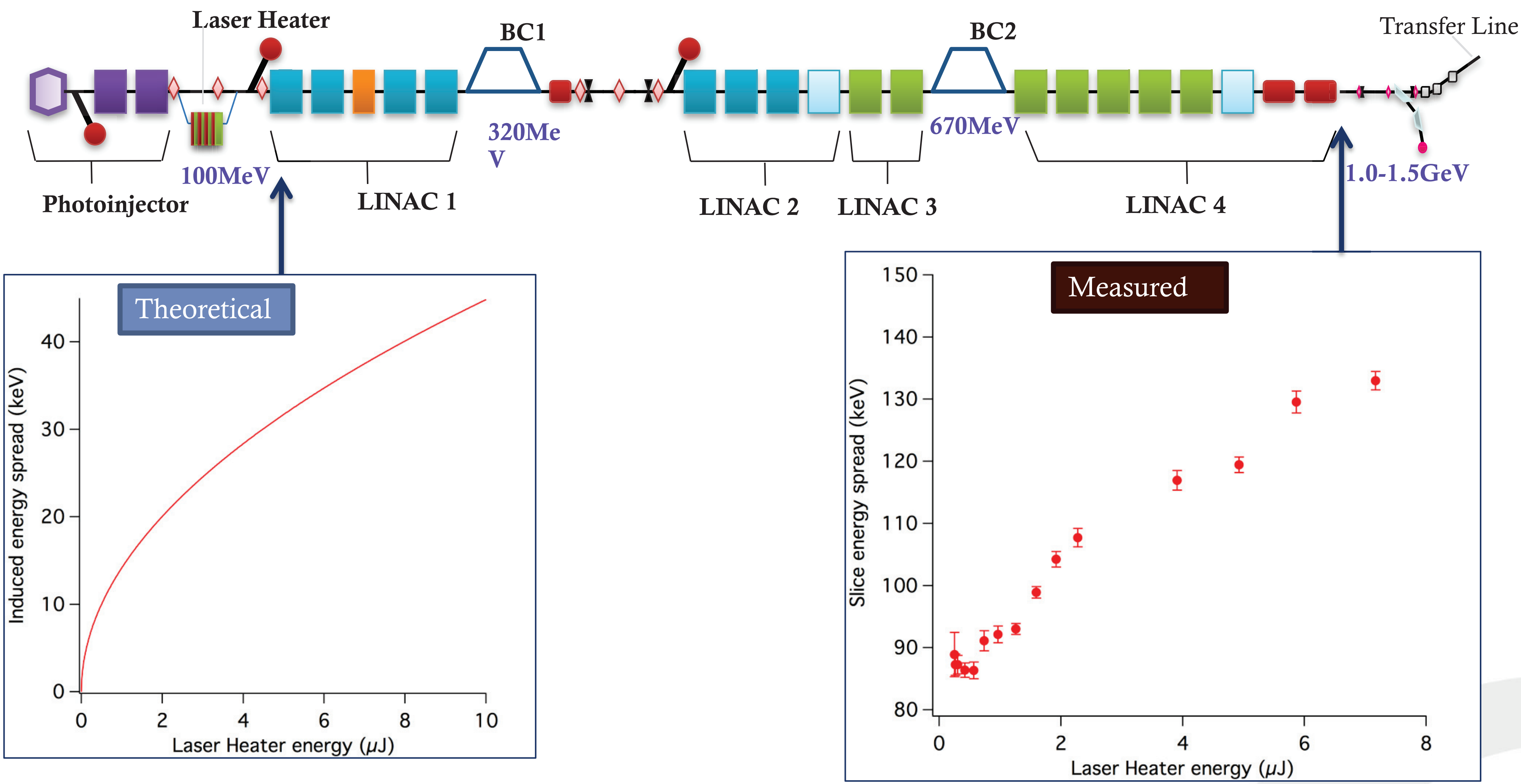

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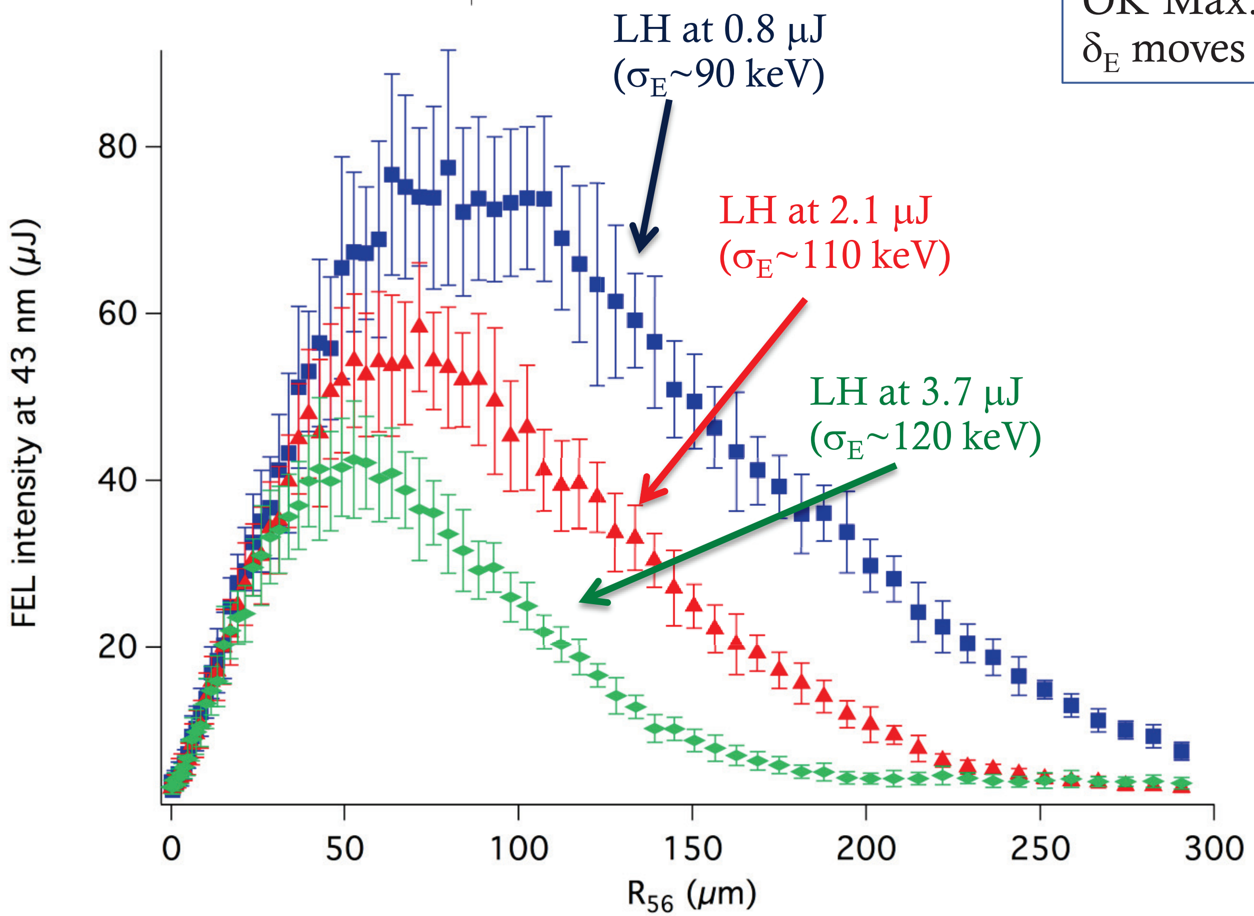
Opt. Kly. performance versus σ_E (2/3)

OK Max. Intensity for $R_{56}k_r\delta_E$~1, so increasing δ_E moves the peak towards smaller R_{56}.



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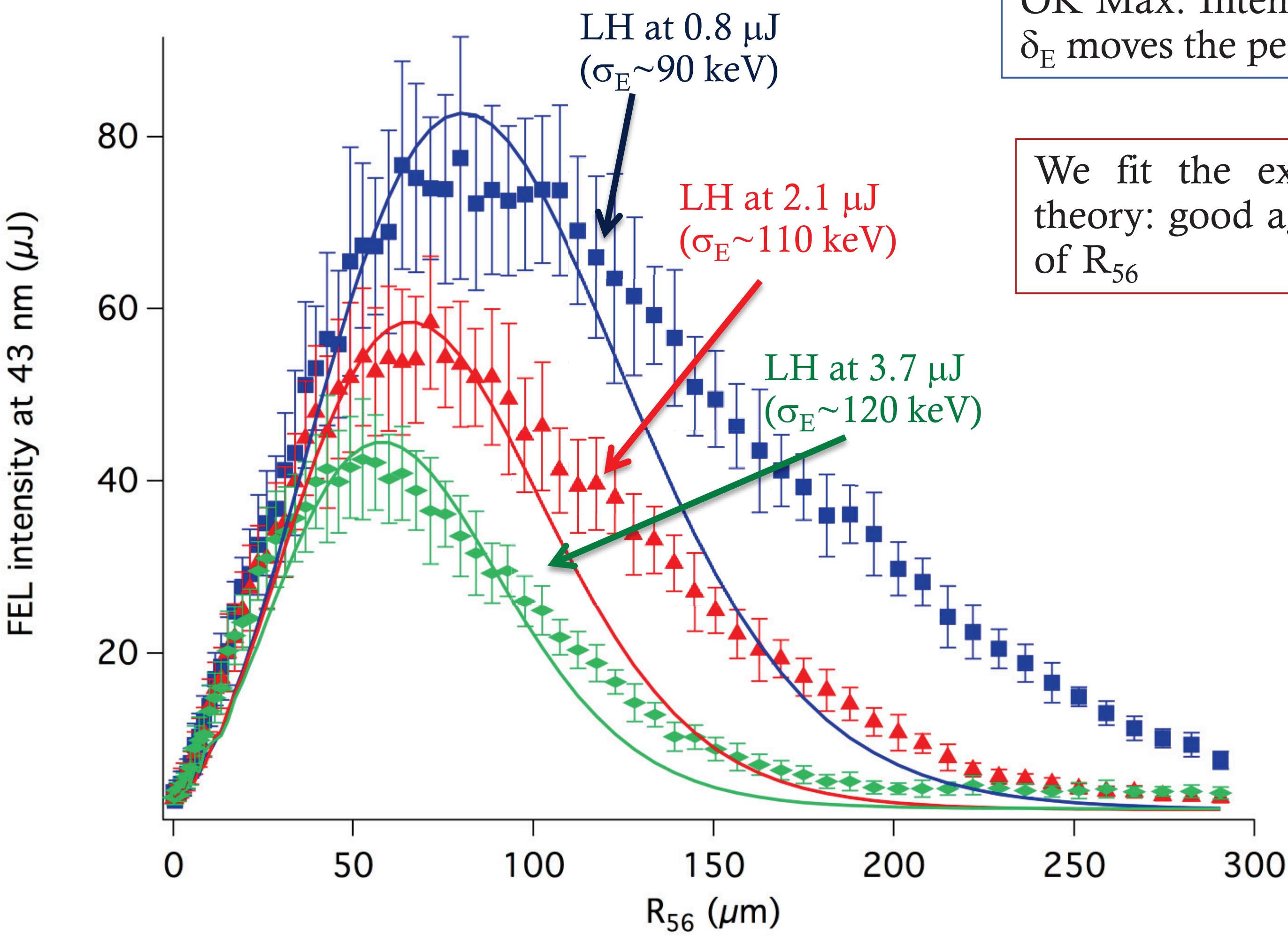
Opt. Kly. performance versus σ_E (2/3)

OK Max. Intensity for $R_{56}k_r\delta_E \sim 1$, so increasing δ_E moves the peak towards smaller R_{56}.

We fit the experimental data with the 1-D theory: good agreement but not for high values of R_{56}



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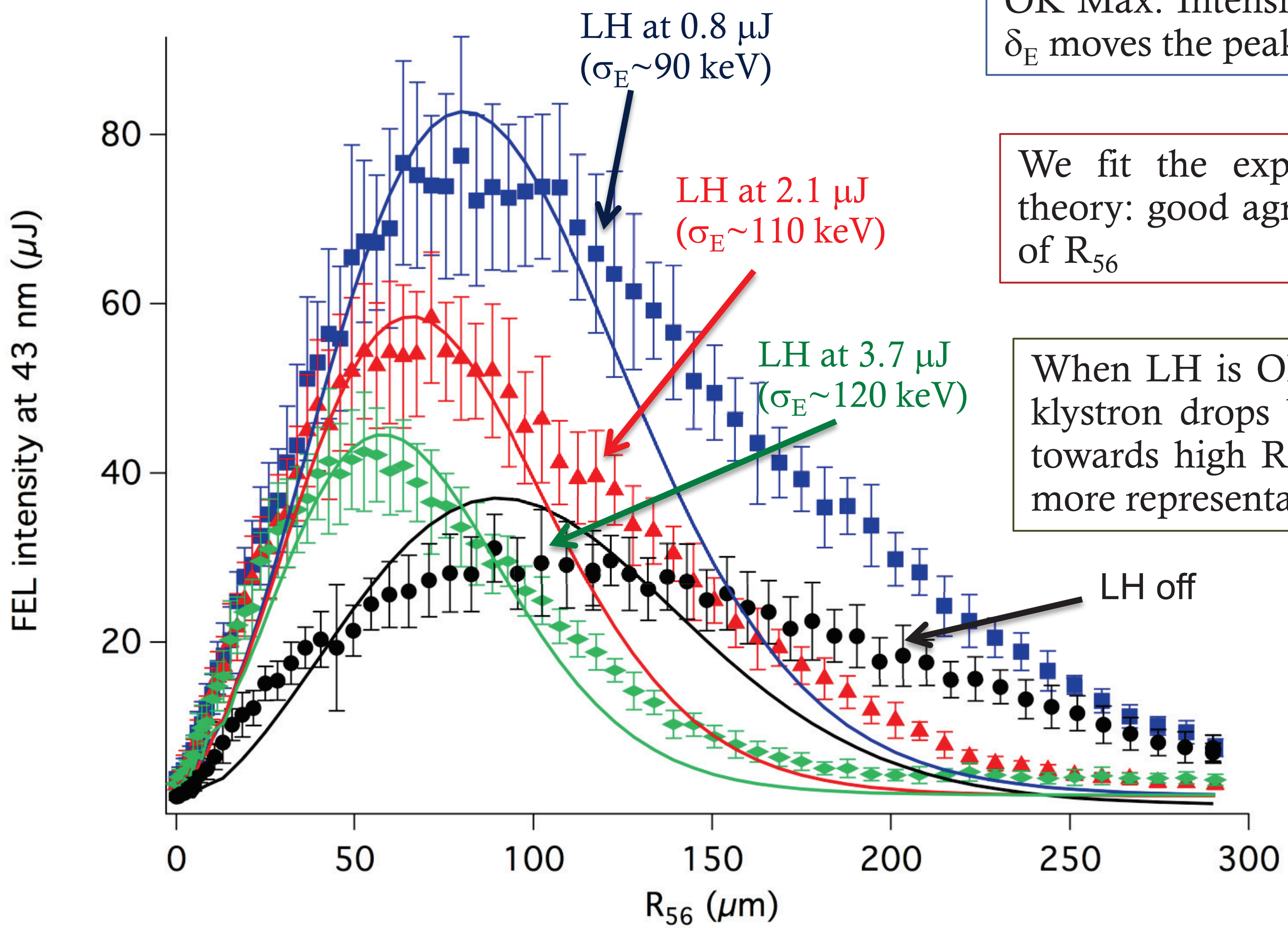
Opt. Kly. performance versus σ_E (2/3)

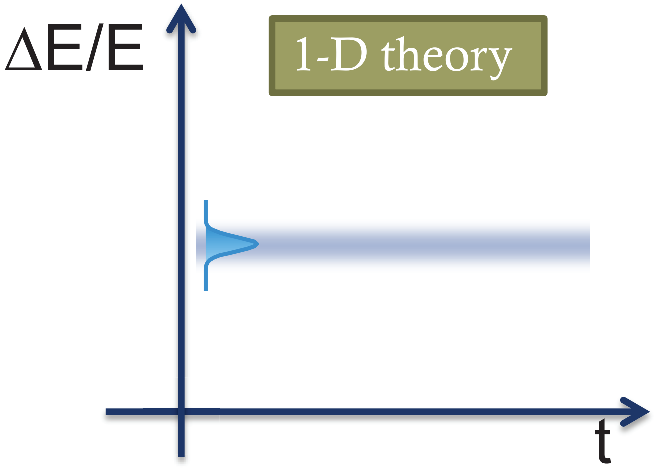
OK Max. Intensity for $R_{56}k_r\delta_E$~1, so increasing δ_E moves the peak towards smaller R_{56}.

We fit the experimental data with the 1-D theory: good agreement but not for high values of R_{56}

When LH is OFF, the efficiency of the optical klystron drops but in the meantime it extends towards high R56 values (the 1-D theory is no more representative)



e-beam longitudinal phase space



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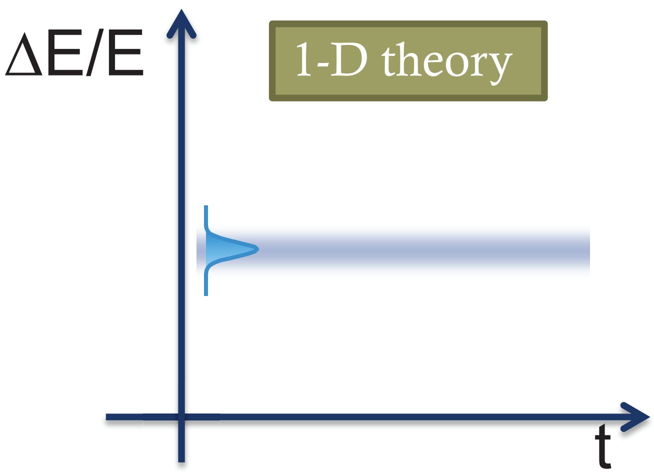
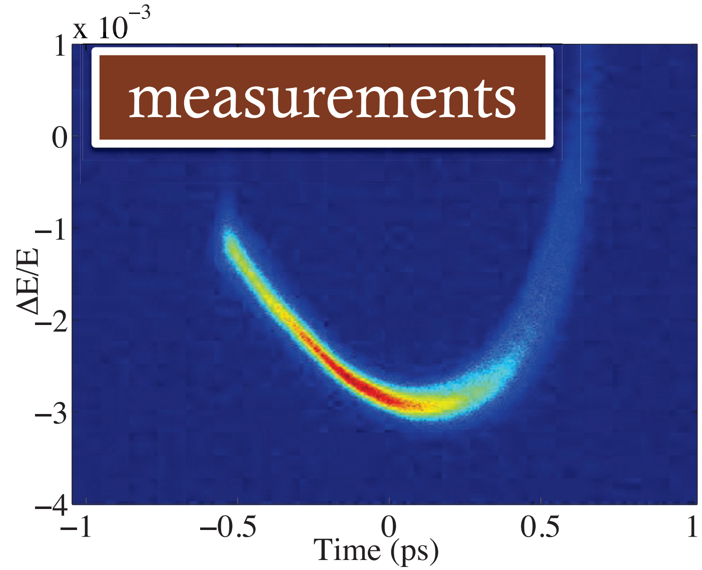
e-beam longitudinal phase space





σ_E is not uniform along the bunch.

Collective effects (e.g. residual microbunching instability) can extend the efficiency of the optical klystron to R56 values larger than expected.

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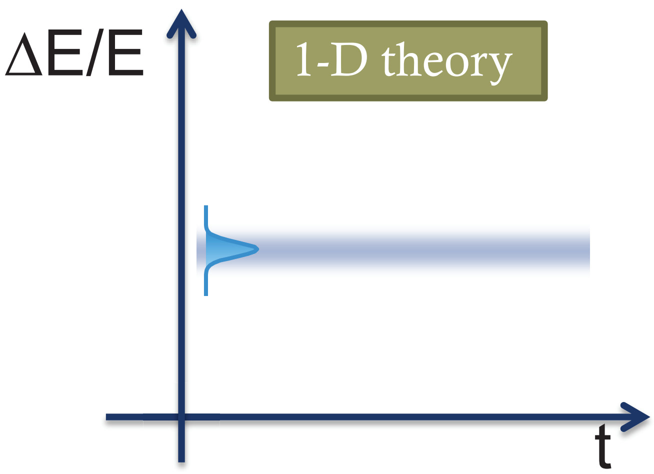
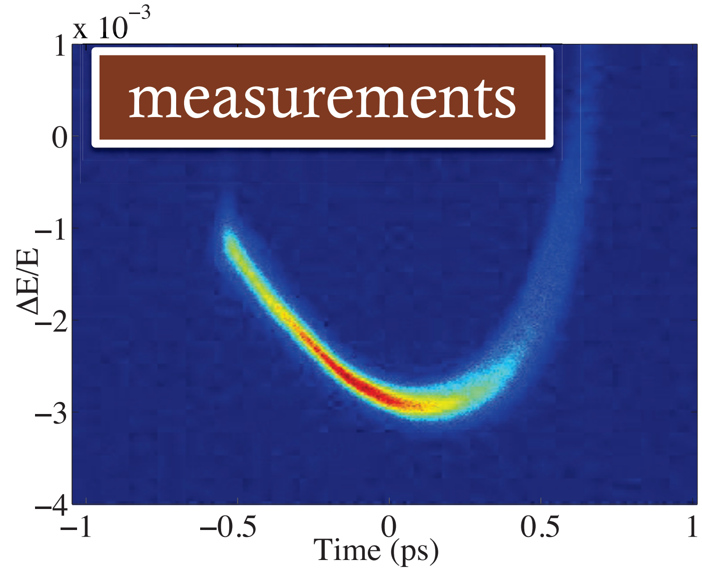
e-beam longitudinal phase space





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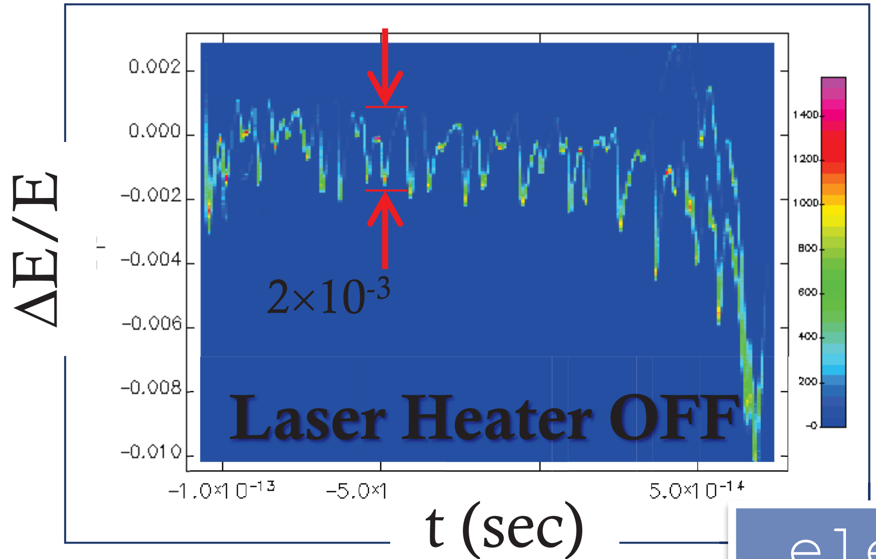

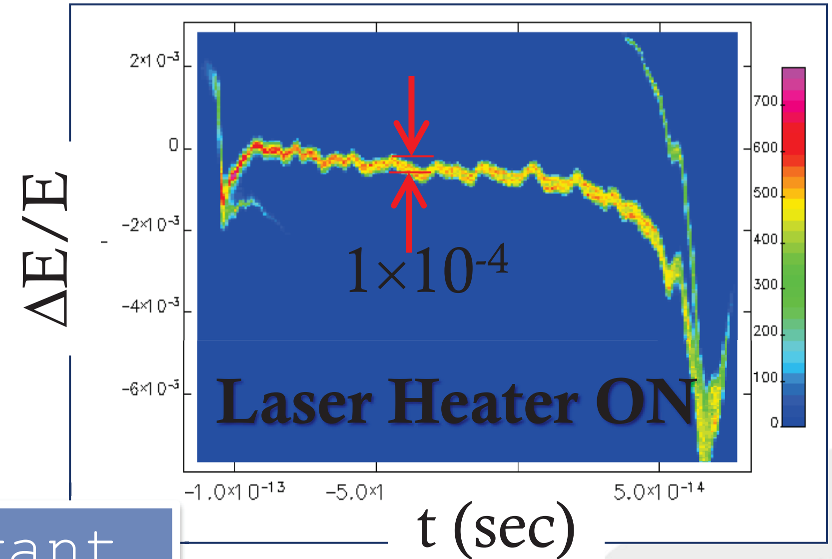

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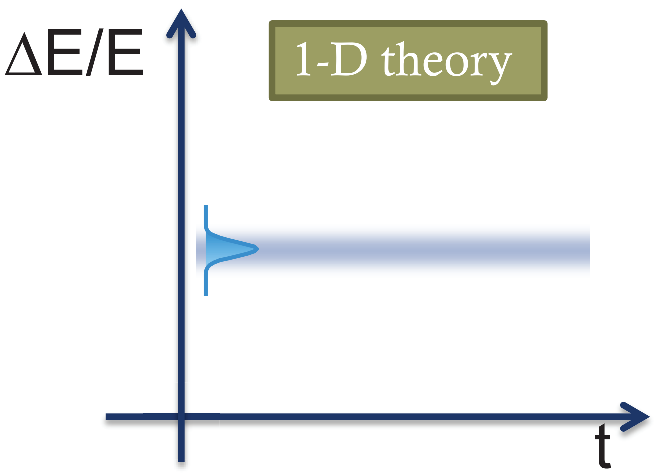
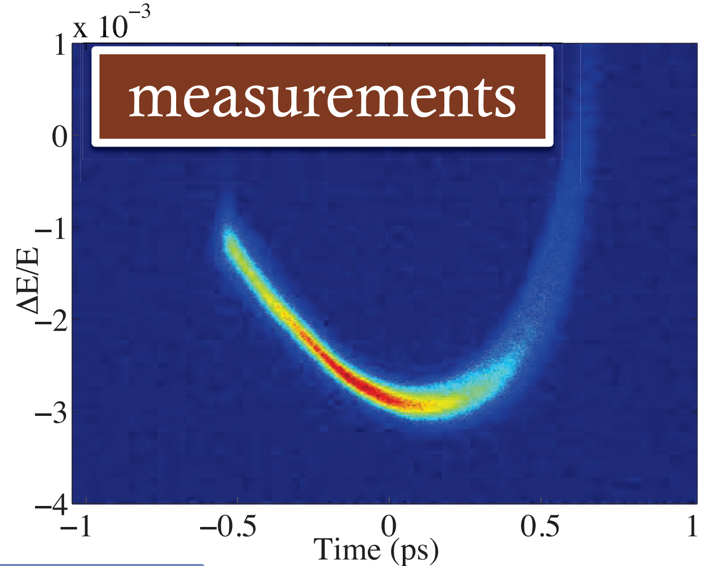
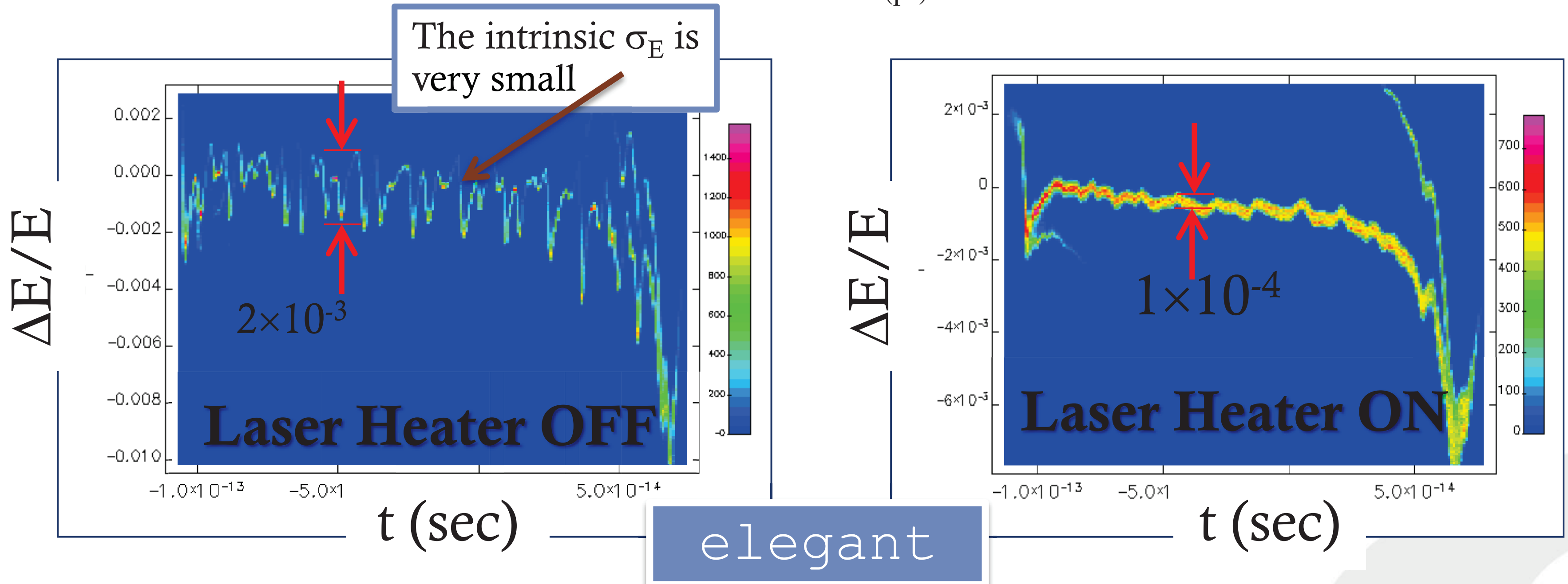
e-beam longitudinal phase space





σ_E is not uniform along the bunch.

Collective effects (e.g. residual microbunching instability) can extend the efficiency of the optical klystron to R56 values larger than expected.



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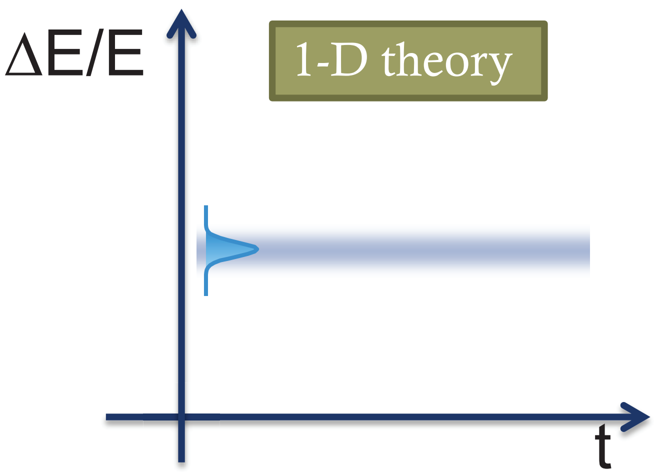
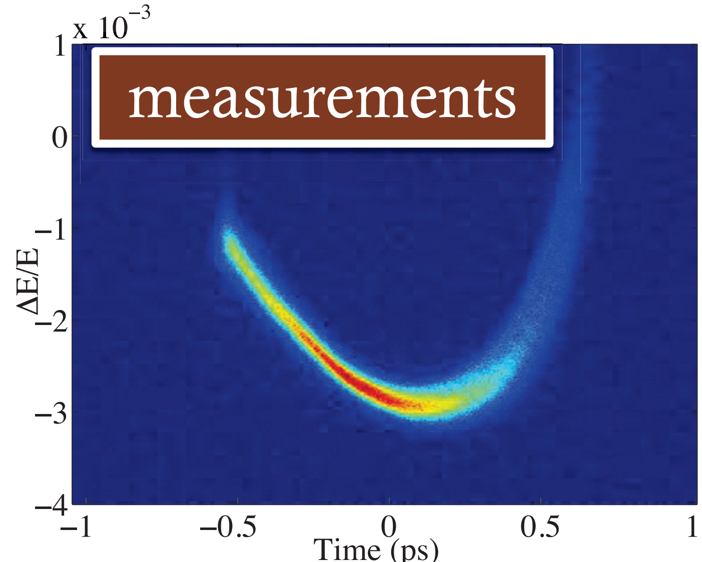
e-beam longitudinal phase space

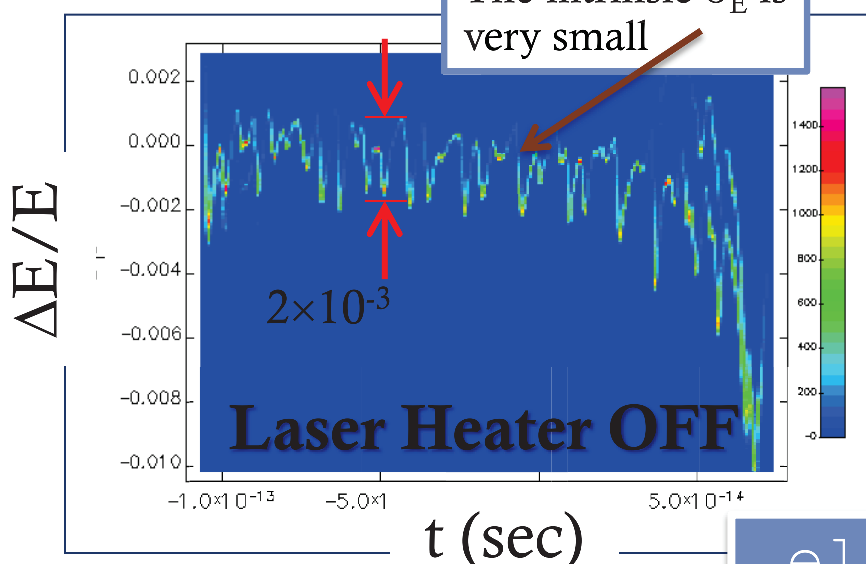




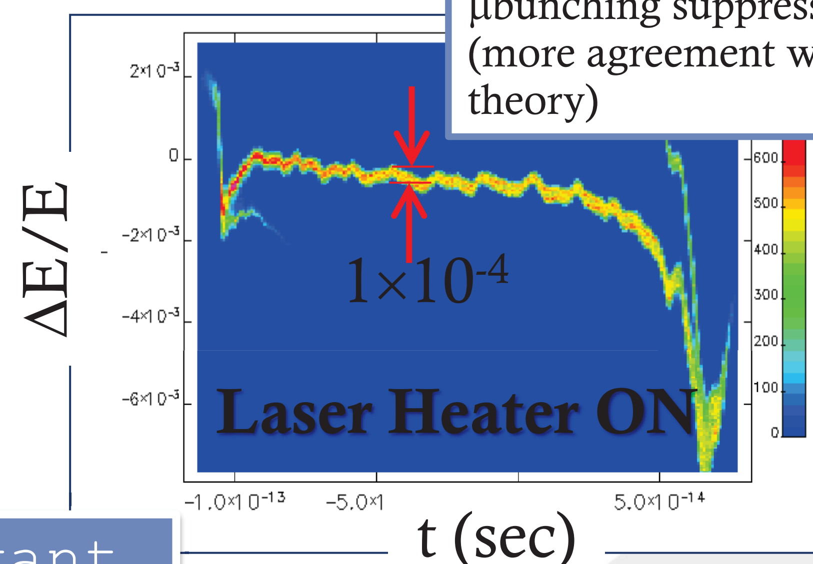
σ_E is not uniform along the bunch.

Collective effects (e.g. residual microbunching instability) can extend the efficiency of the optical klystron to R56 values larger than expected.

The intrinsic σ_E is very small



The intrinsic σ_E was increased by LH and μbunching suppressed (more agreement with 1D theory)



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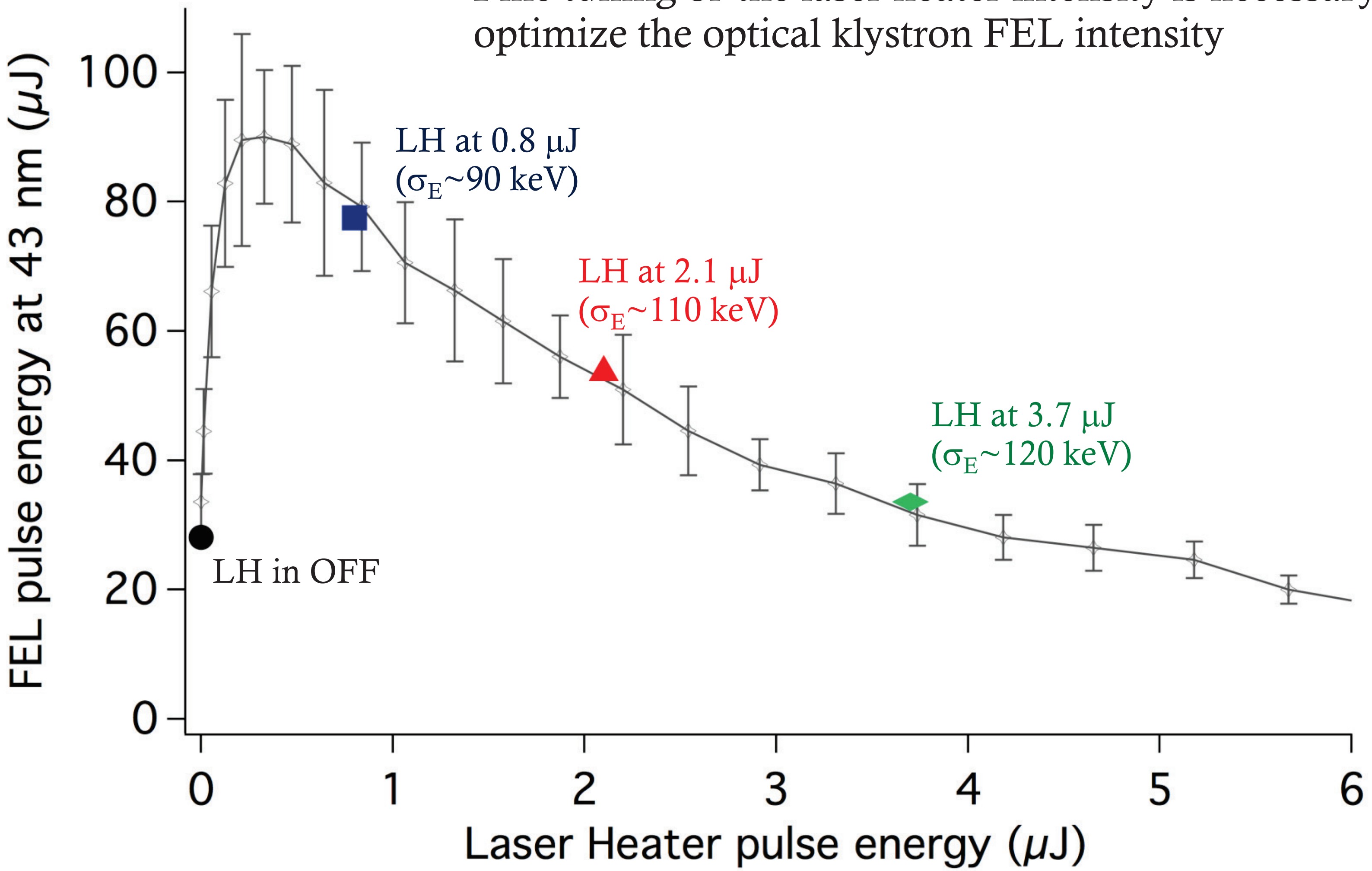
Opt. Kly. performance versus σ_E (3/3)

- Fine tuning of the laser heater intensity is necessary to optimize the optical klystron FEL intensity



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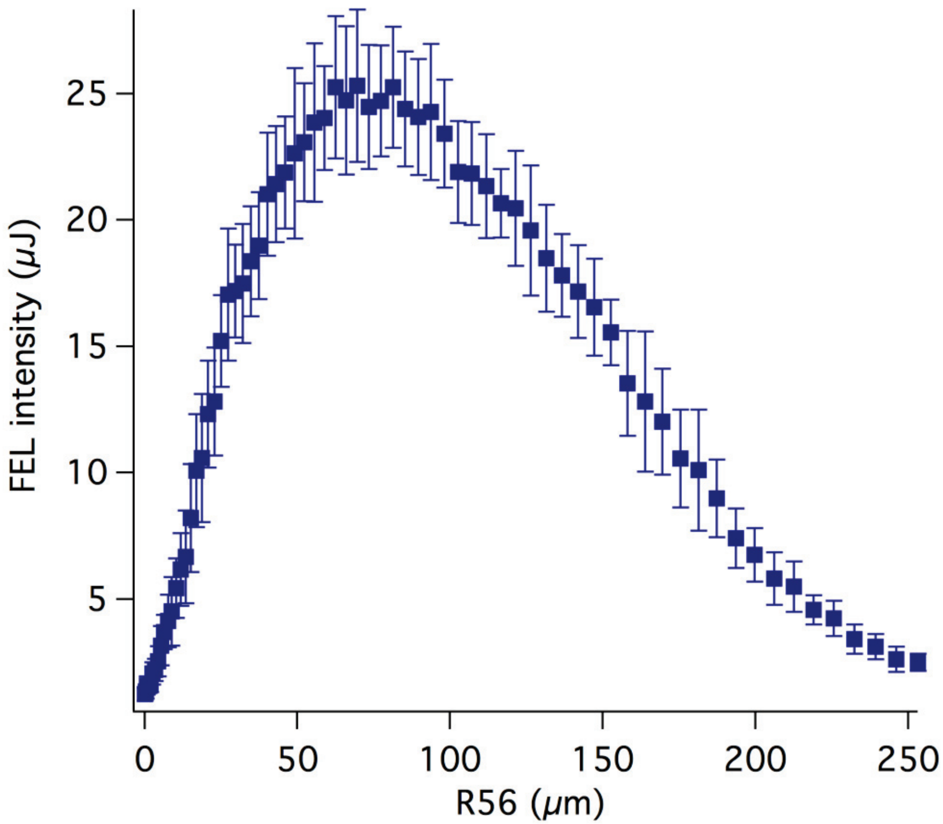
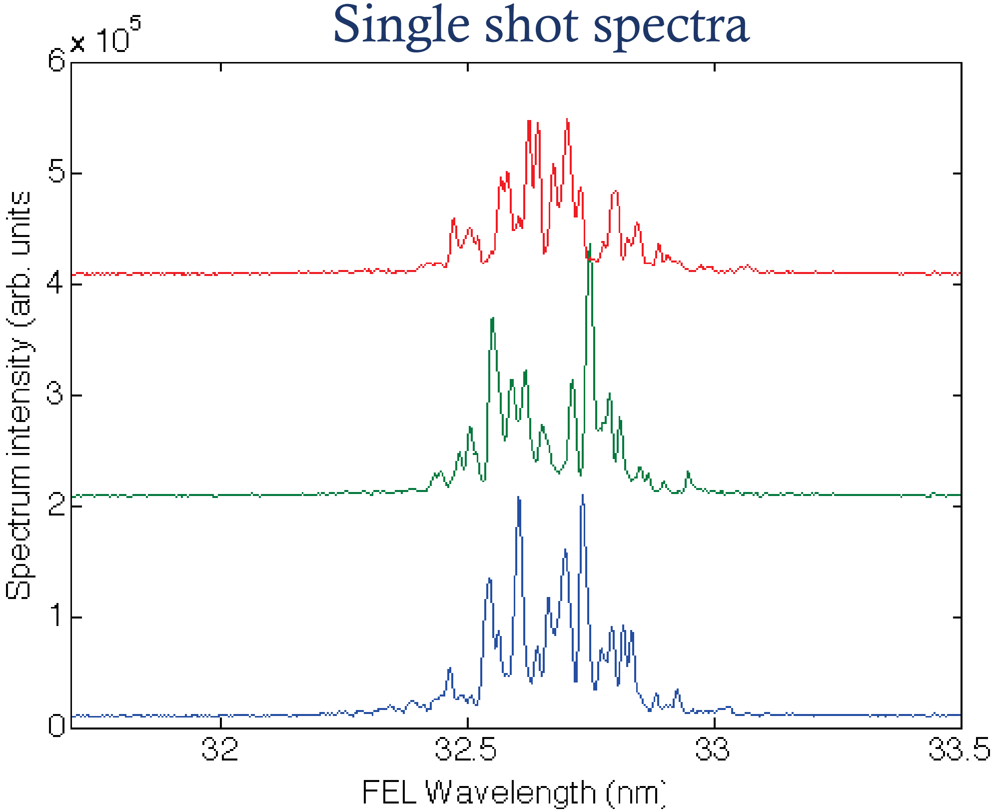
Optical Klystron FEL at 32 nm



Single shot spectra



Intensity stability ~ 10% (rms)

σ_λ/λ~0.3%~2ρ

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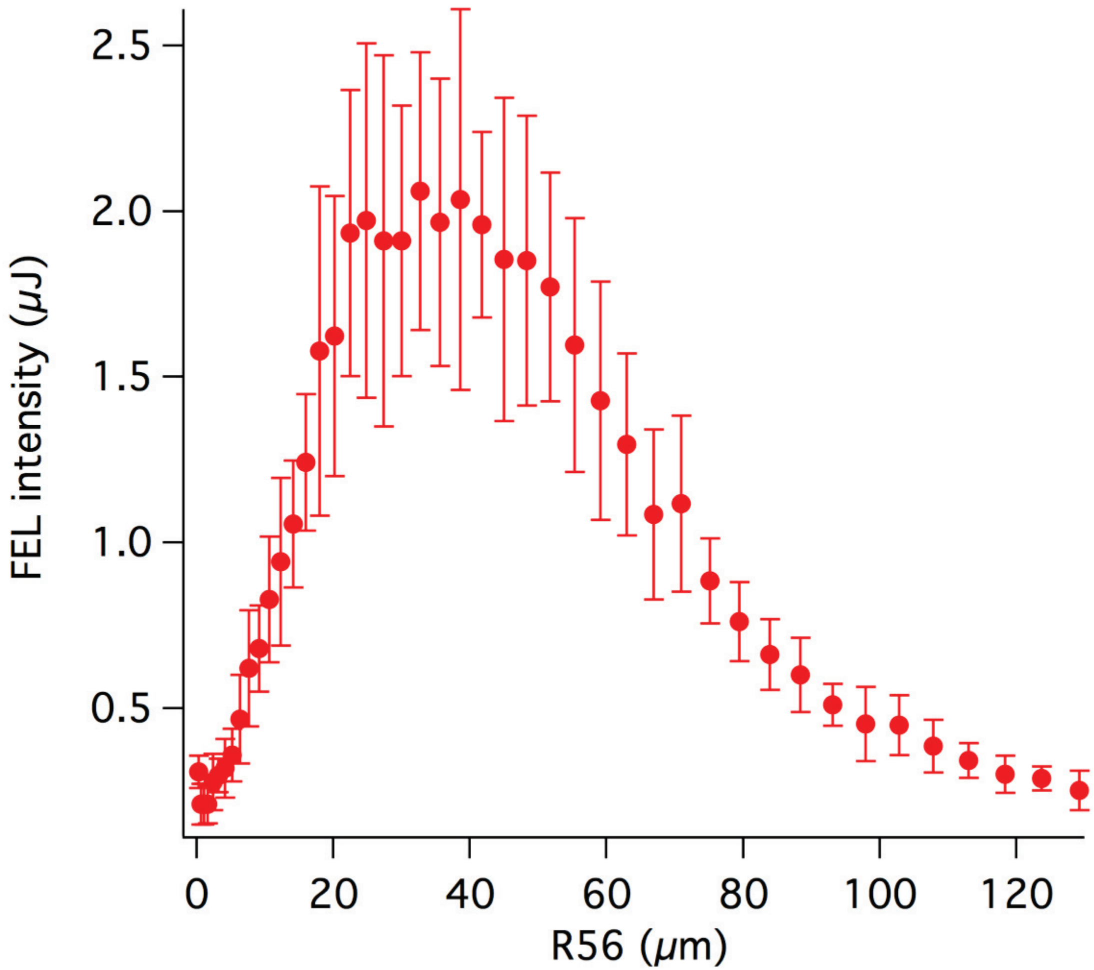
Optical Klystron FEL at 20 nm



Intensity stability ~ 20% (rms)

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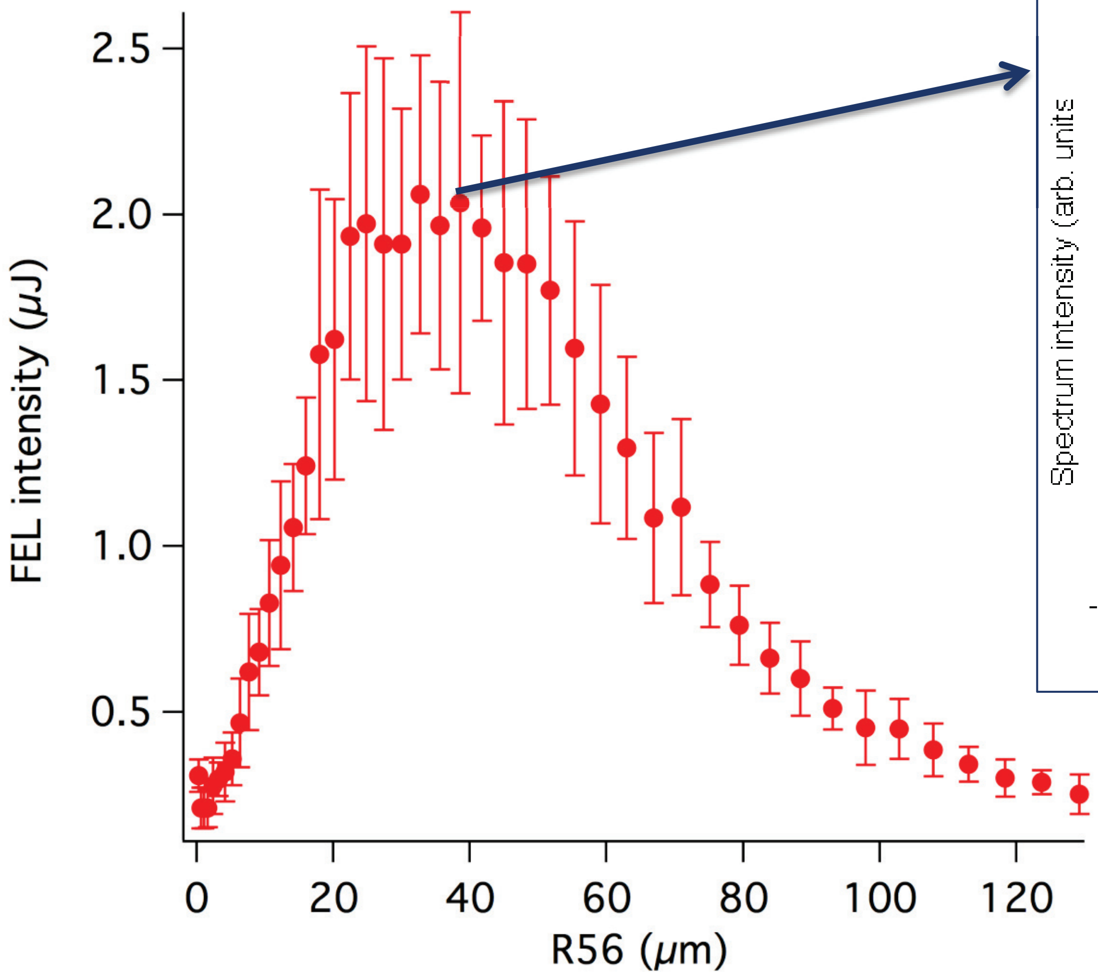
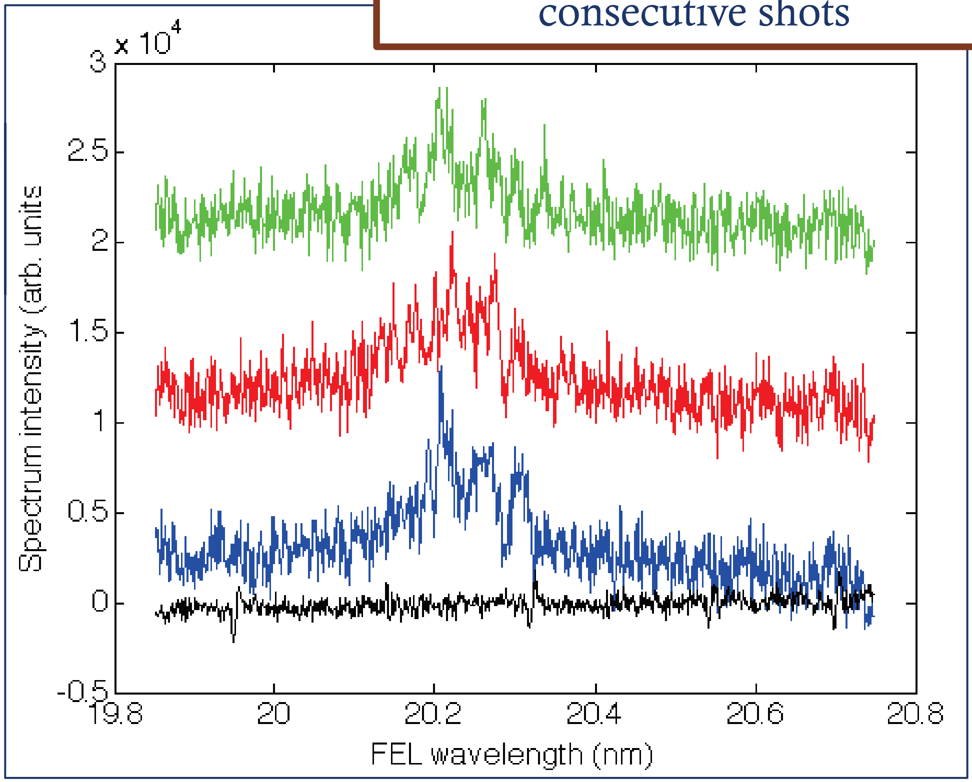
Optical Klystron FEL at 20 nm



Averaged spectrum over 5 consecutive shots



Intensity stability ~ 20% (rms)

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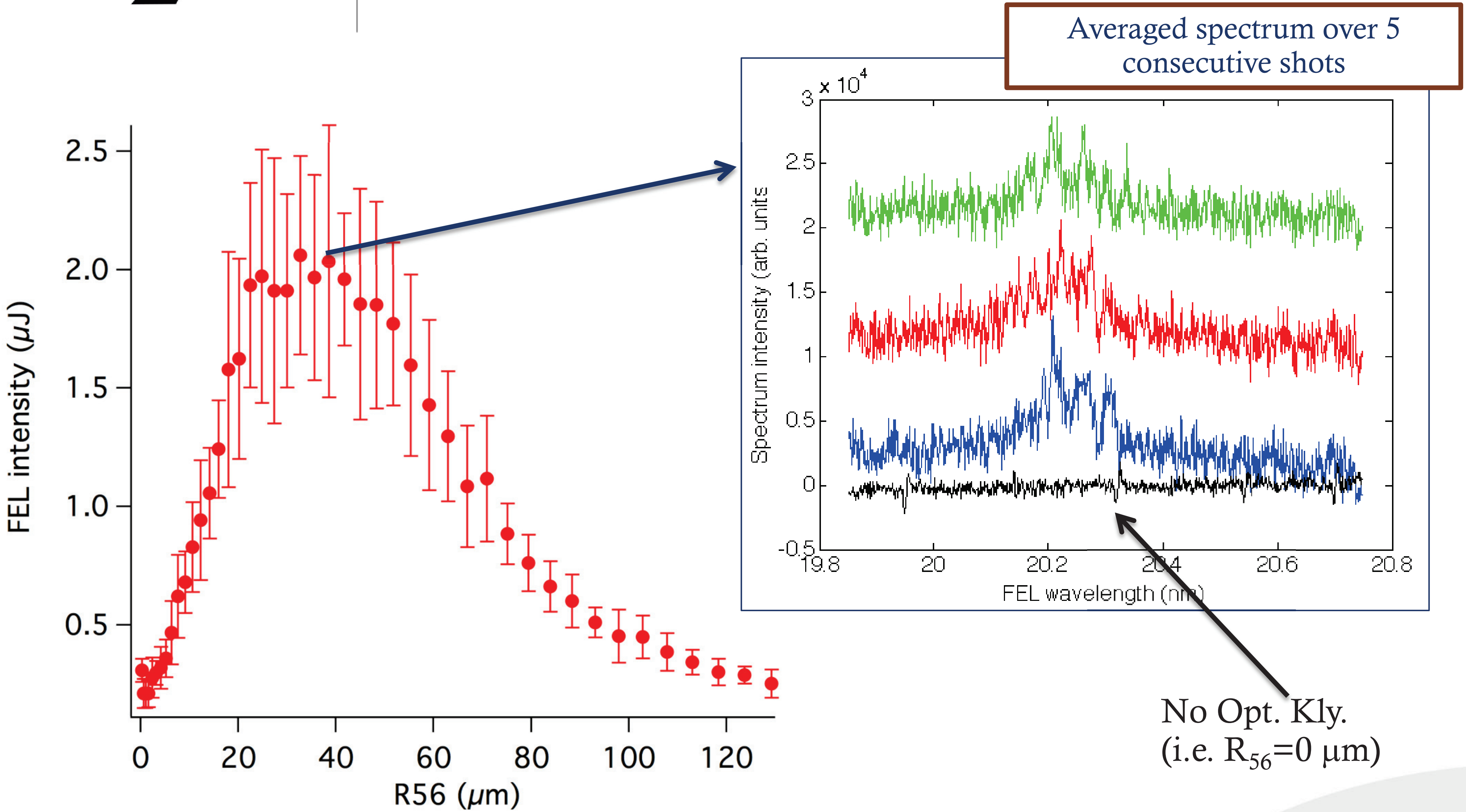
Optical Klystron FEL at 20 nm



Intensity stability ~ 20% (rms)

$\sigma_\lambda/\lambda \sim 0.3\% \sim 3\rho$

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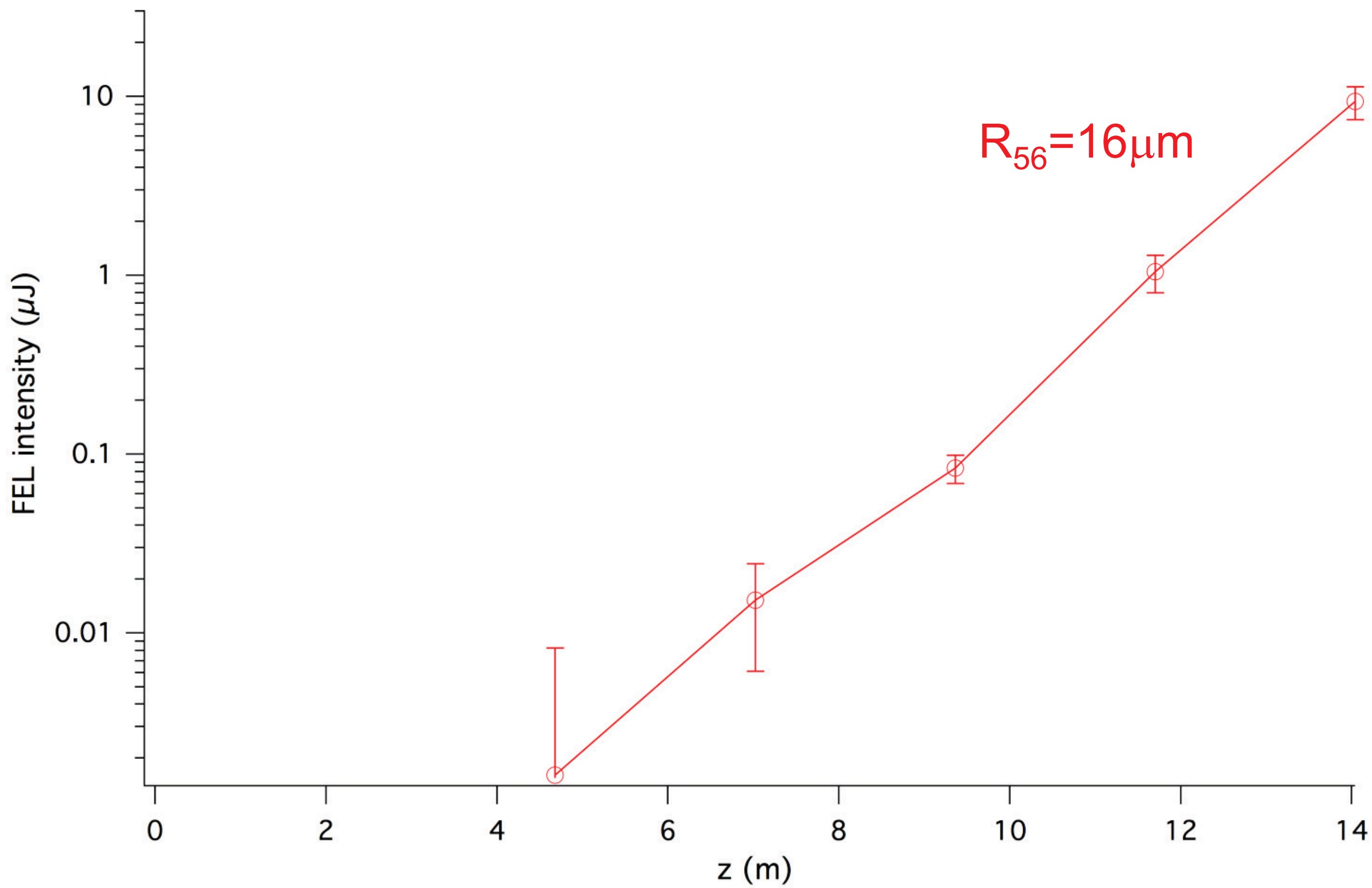
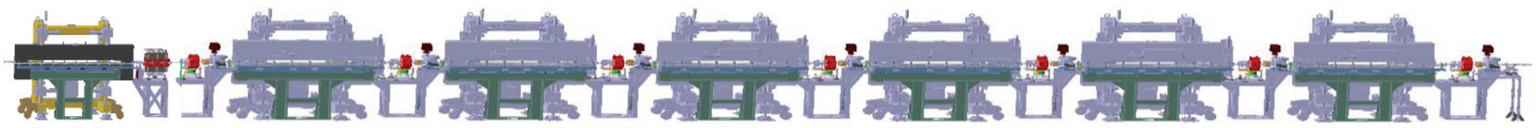
Gain Curve: OK vs Seeded HGHG (at 32nm)





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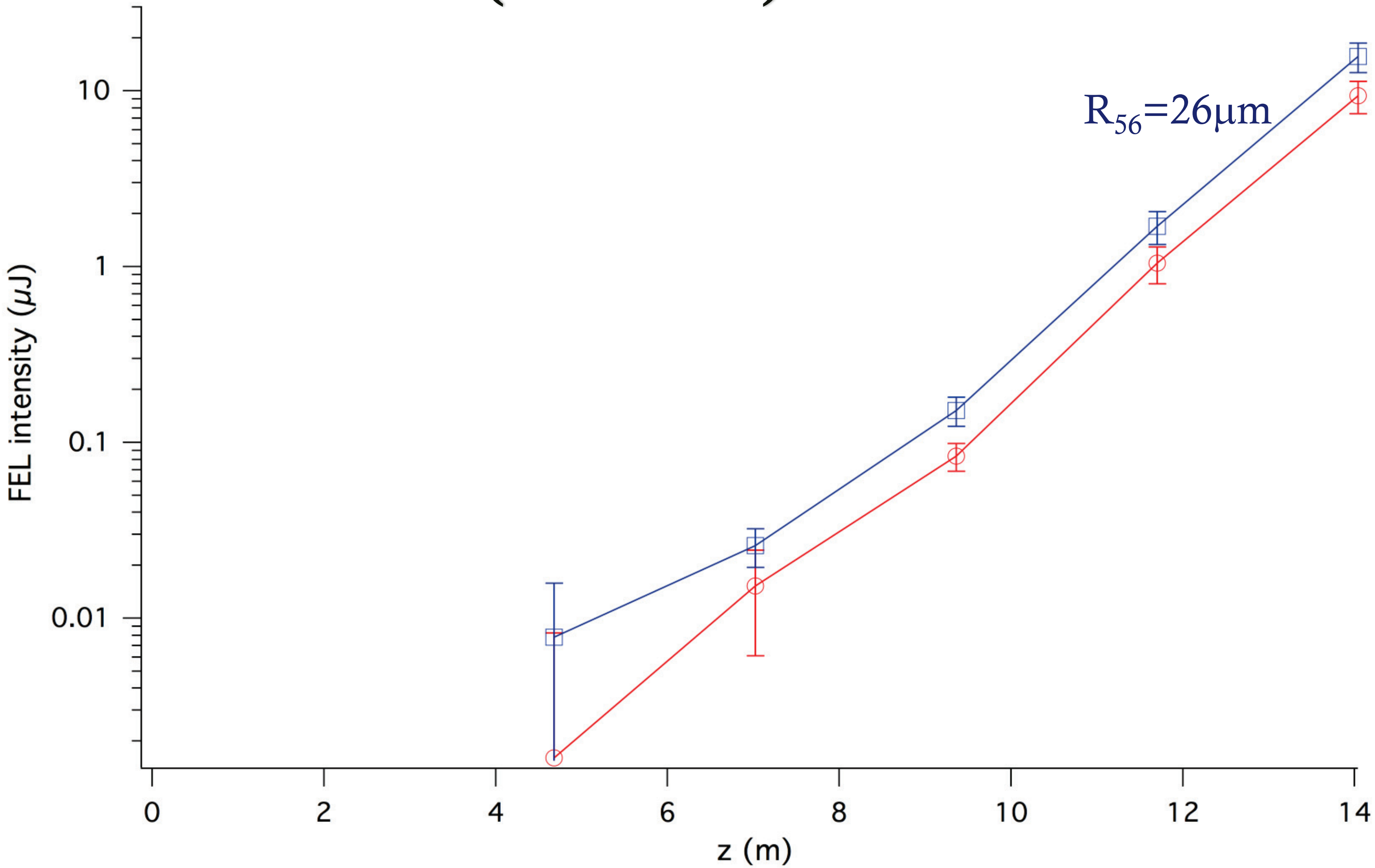

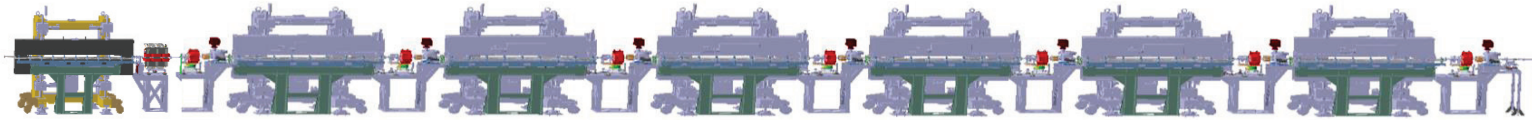

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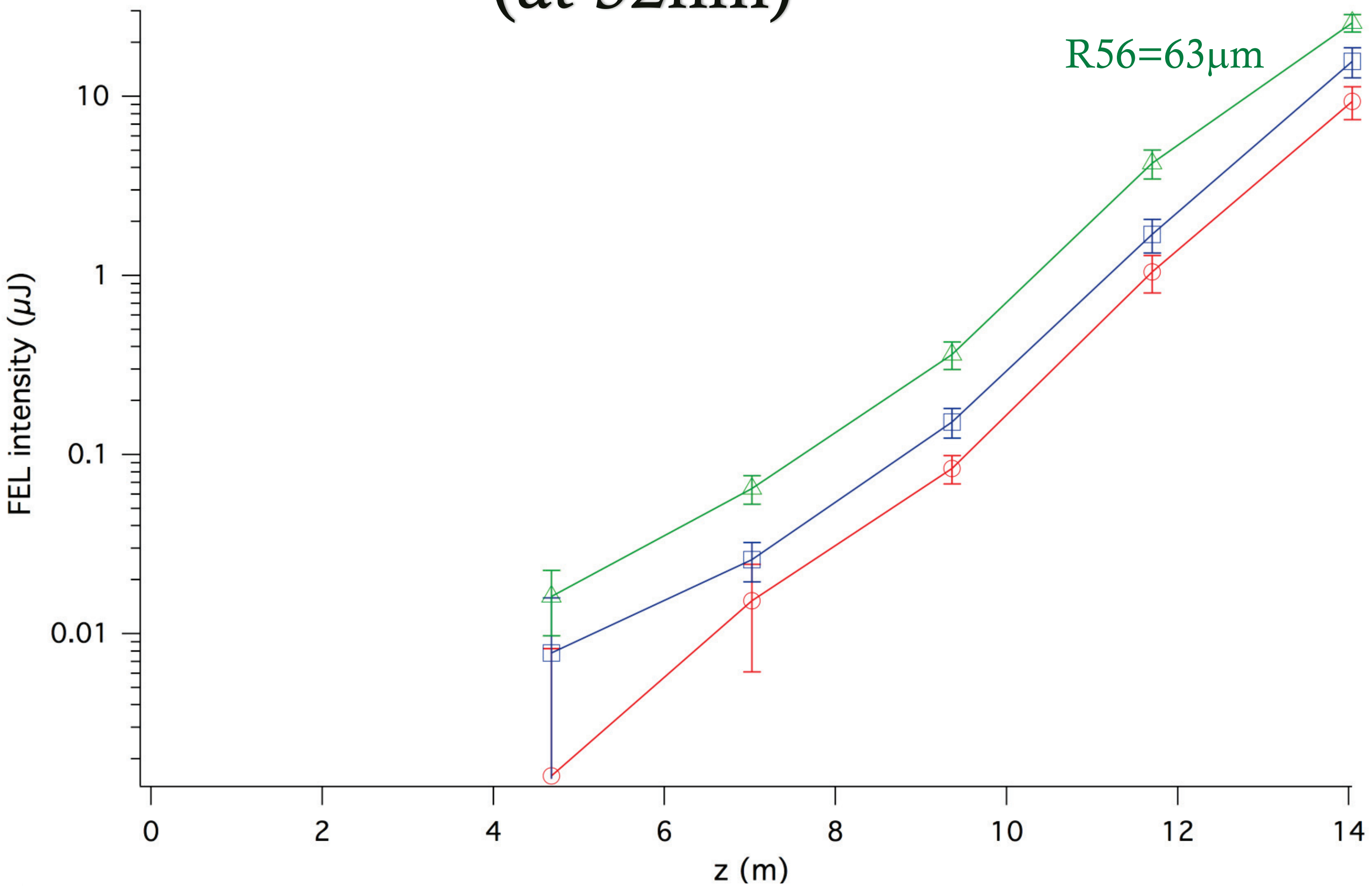

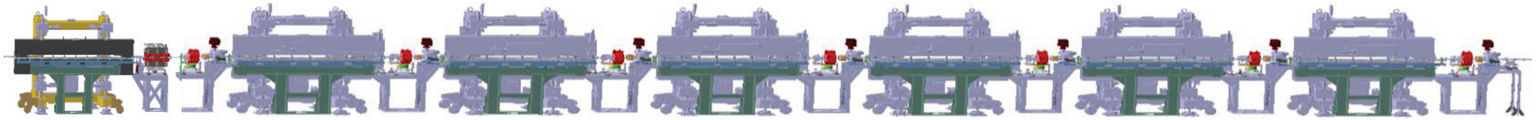

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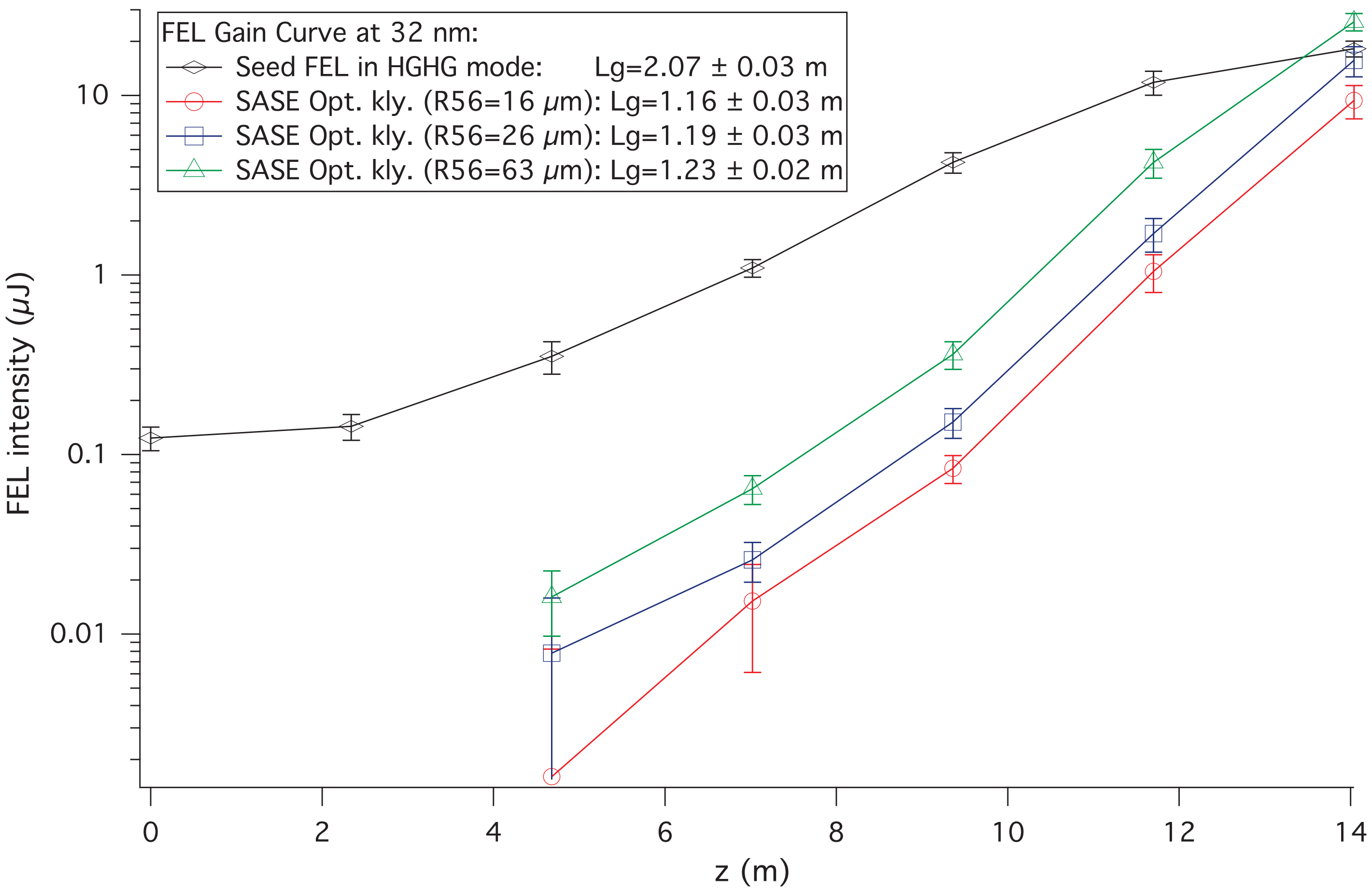

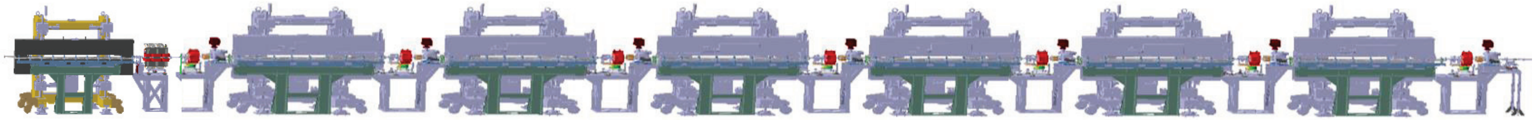

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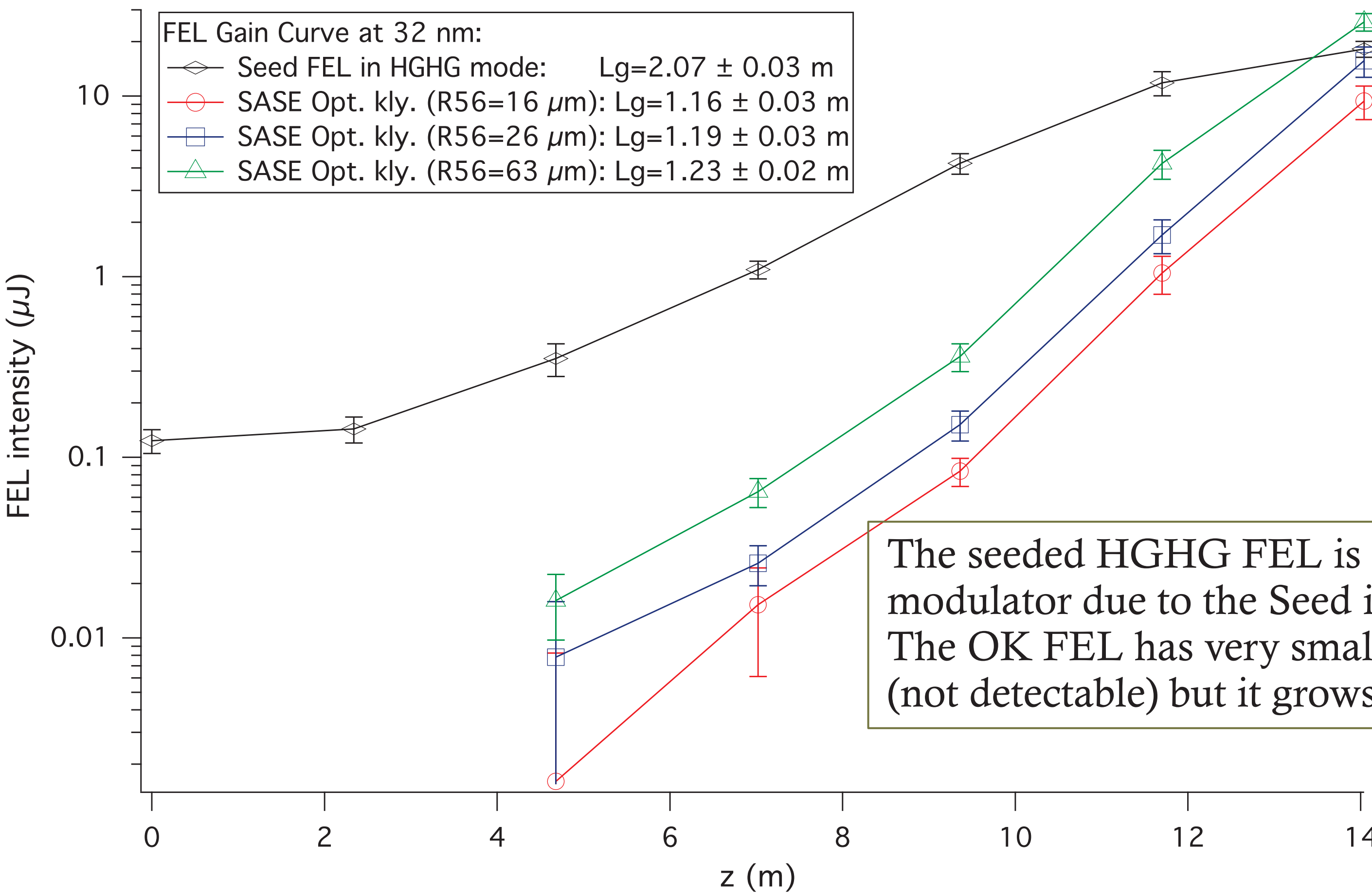
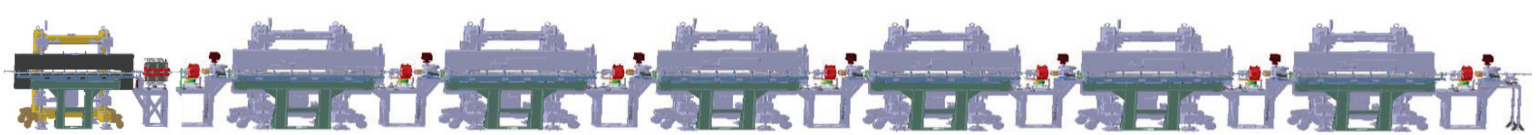
Sincrotrone
Trieste

Gain Curve: OK vs Seeded HGHG (at 32nm)



The seeded HGHG FEL is more intense just after the modulator due to the Seed induced bunching, **(Lg ~2.1 m)**. The OK FEL has very small intensity before the 2nd radiator (not detectable) but it grows more rapidly **(Lg~1.2m)**.



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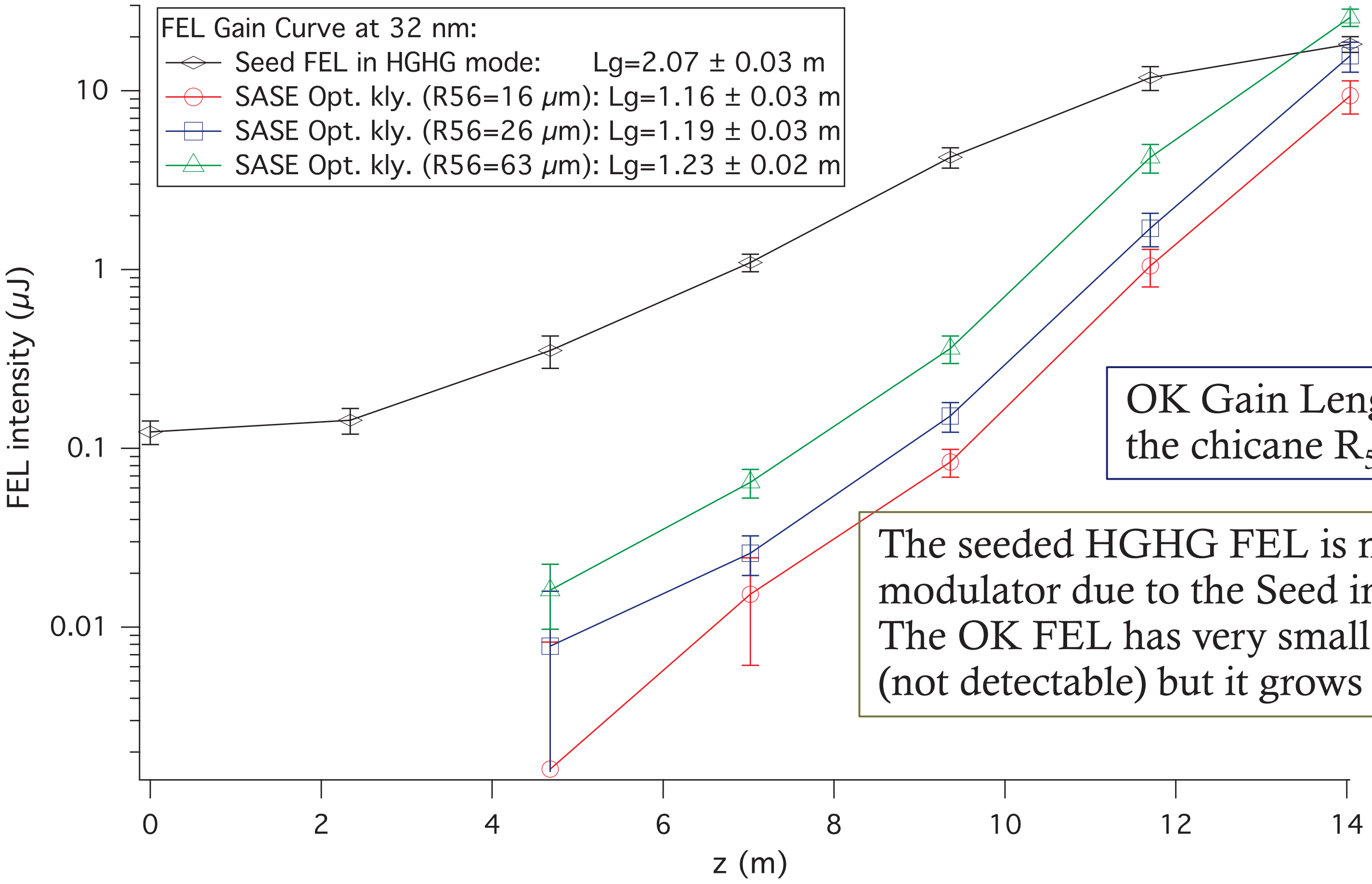
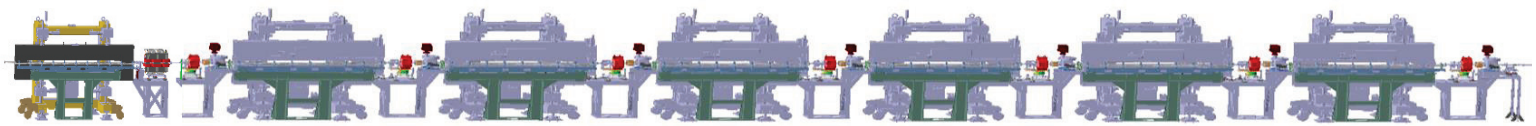
Gain Curve: OK vs Seeded HGHG (at 32nm)



OK Gain Length is independent from the chicane R_{56} as theoretically expected.

The seeded HGHG FEL is more intense just after the modulator due to the Seed induced bunching, **(Lg ~2.1 m)**. The OK FEL has very small intensity before the 2nd radiator (not detectable) but it grows more rapidly **(Lg~1.2m)**.



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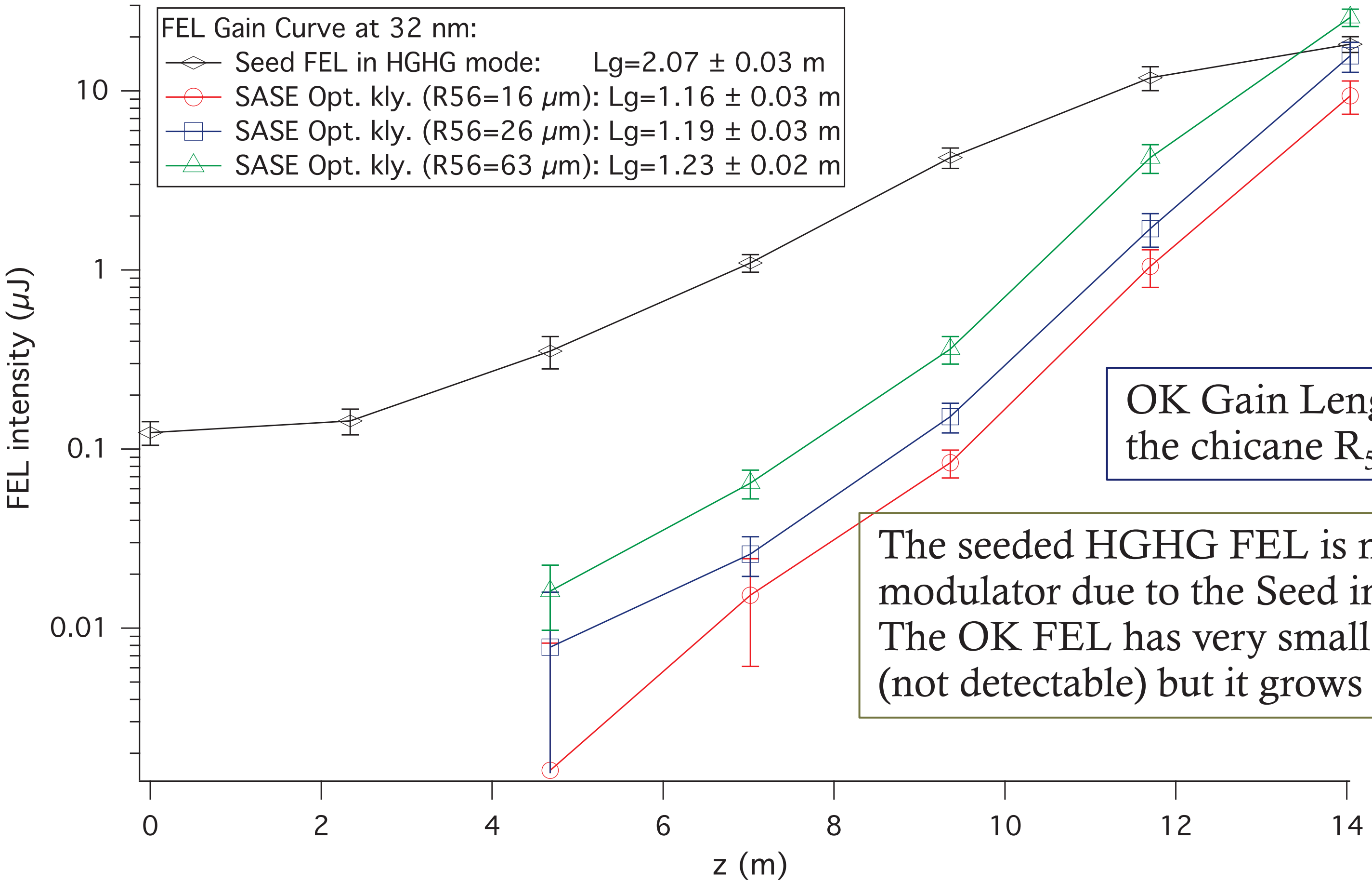
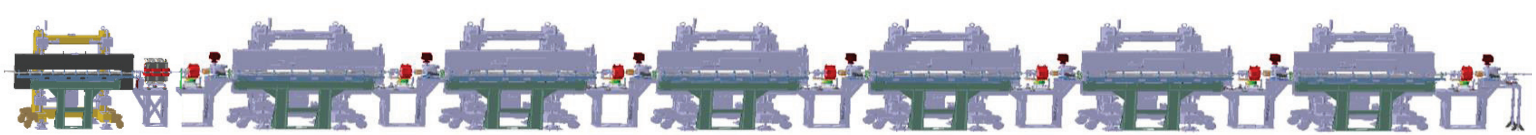
Gain Curve: OK vs Seeded HGHG (at 32nm)



OK uses the whole bunch (~300fs) while HGHG only ~100fs, so at saturation the OK FEL intensity would be higher

OK Gain Length is independent from the chicane R_{56} as theoretically expected.

The seeded HGHG FEL is more intense just after the modulator due to the Seed induced bunching, **(Lg ~2.1 m)**. The OK FEL has very small intensity before the 2nd radiator (not detectable) but it grows more rapidly **(Lg~1.2m)**.



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Spectrum: Opt. Kly. versus HGHG

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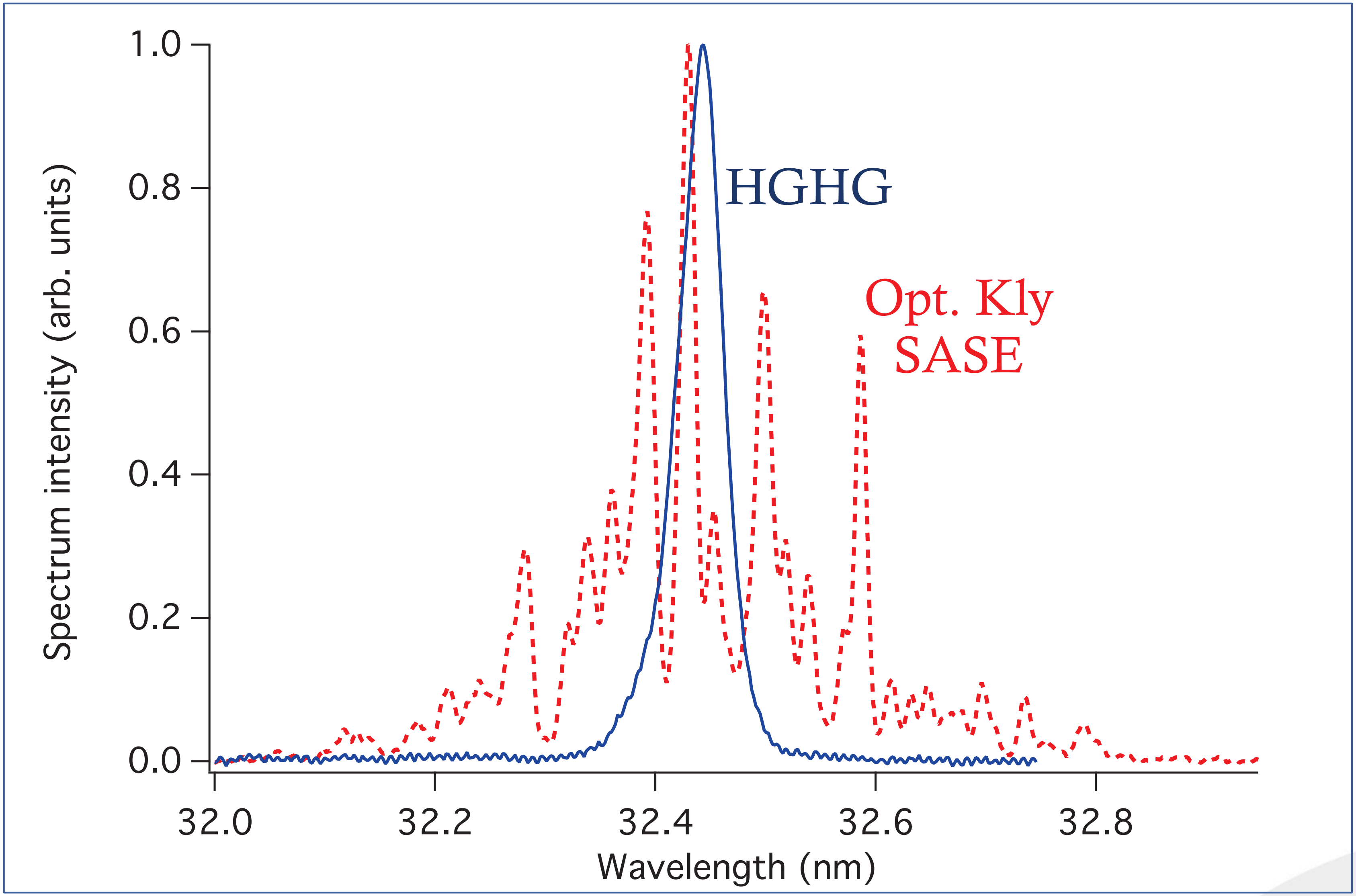

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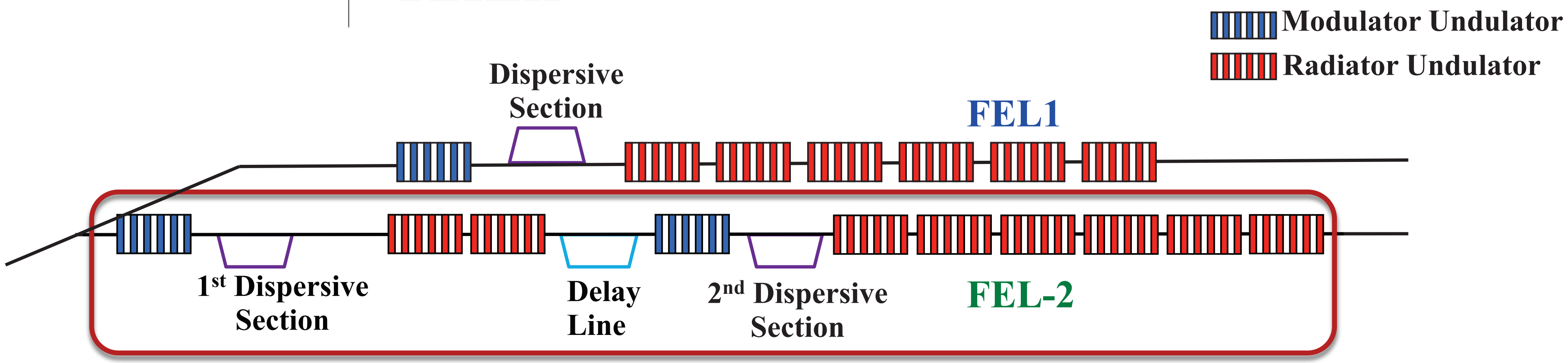
Opt. Kly. Experiment on FEL-2: 12nm



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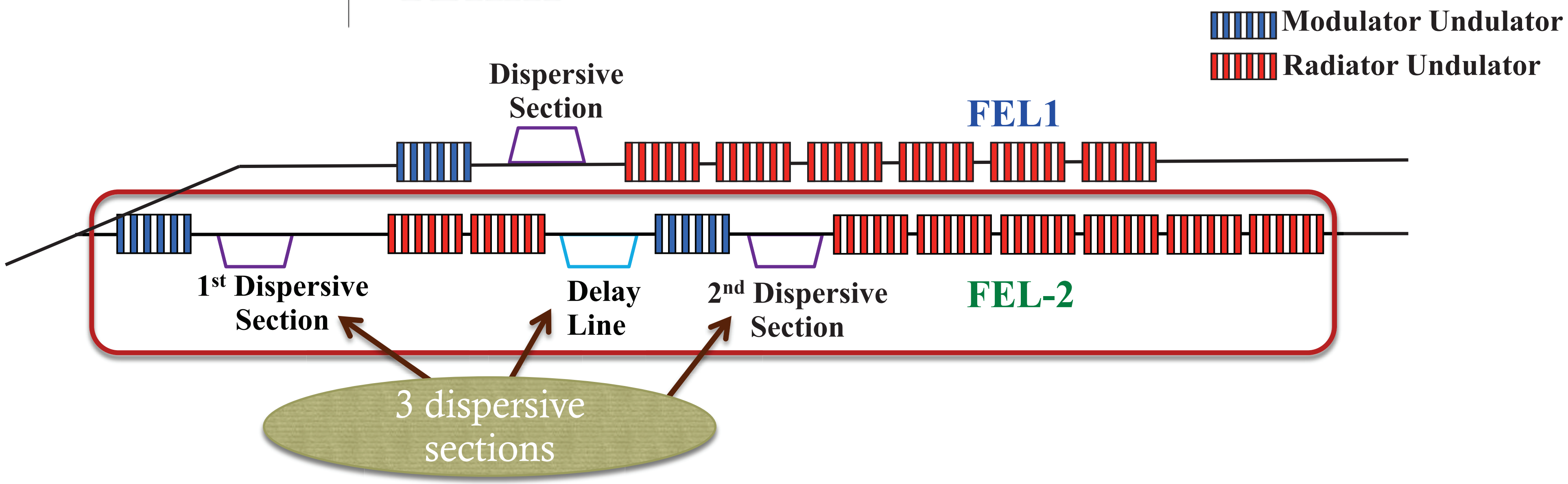
Opt. Kly. Experiment on FEL-2: 12nm



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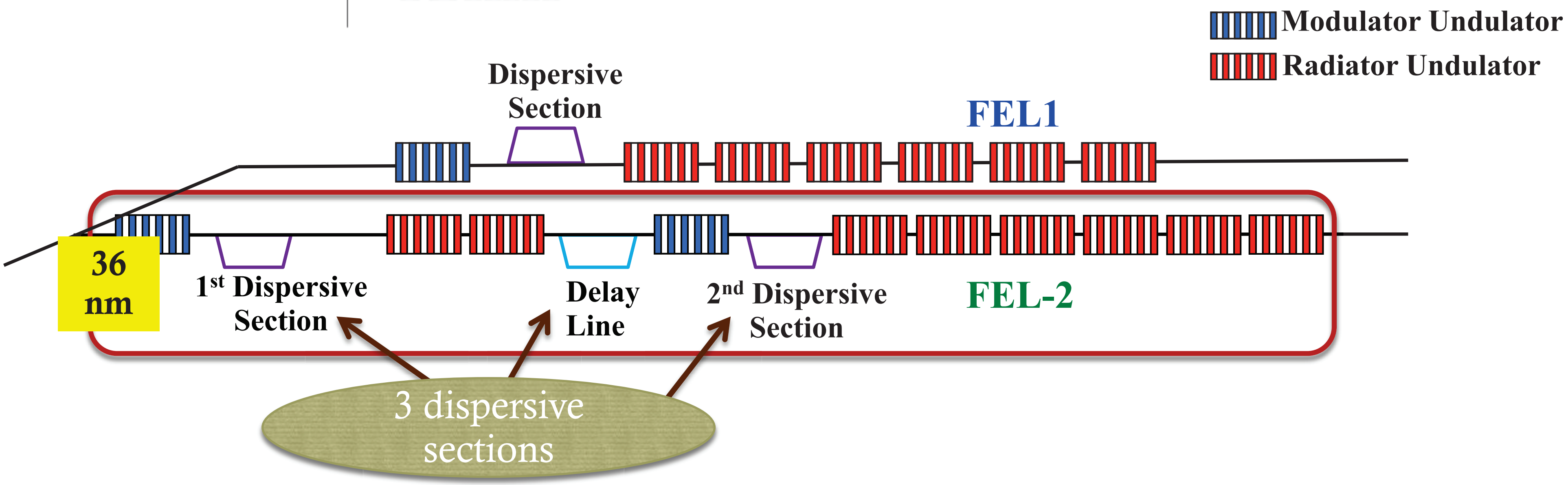
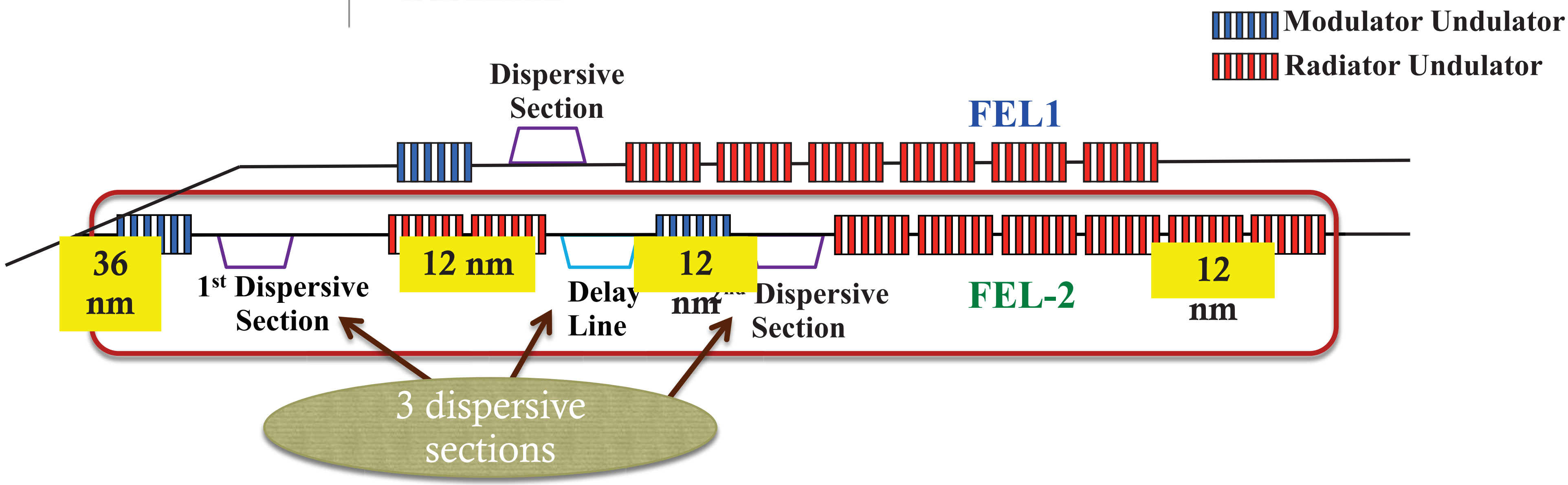
Opt. Kly. Experiment on FEL-2: 12nm



Opt. Kly. Experiment on FEL-2: 12nm



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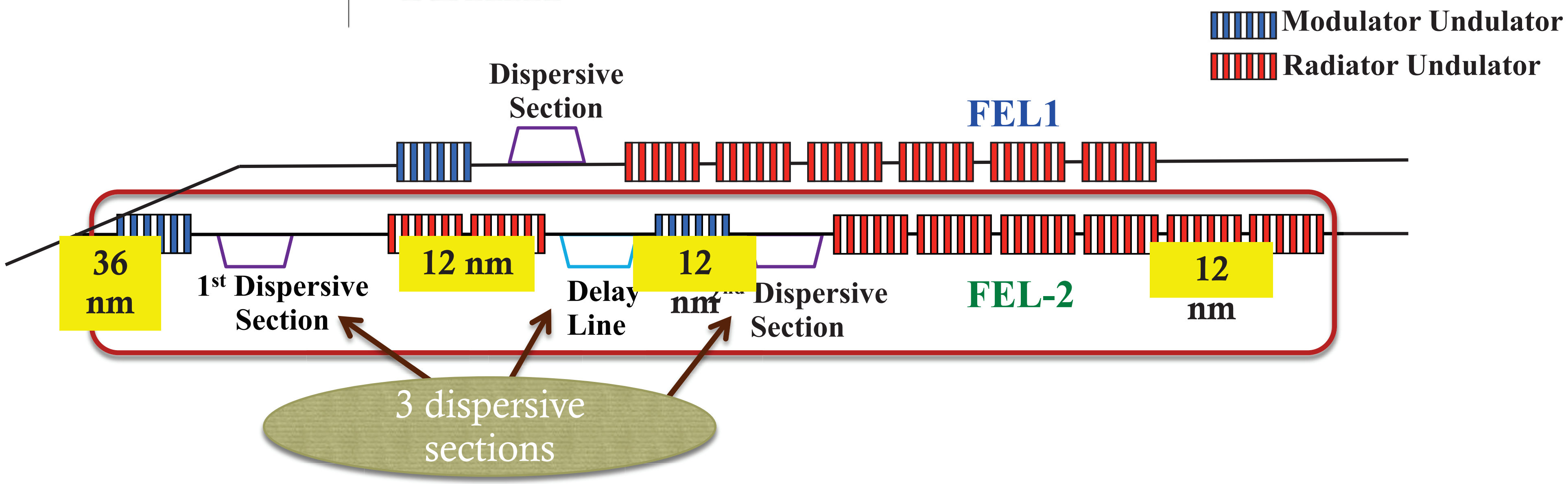

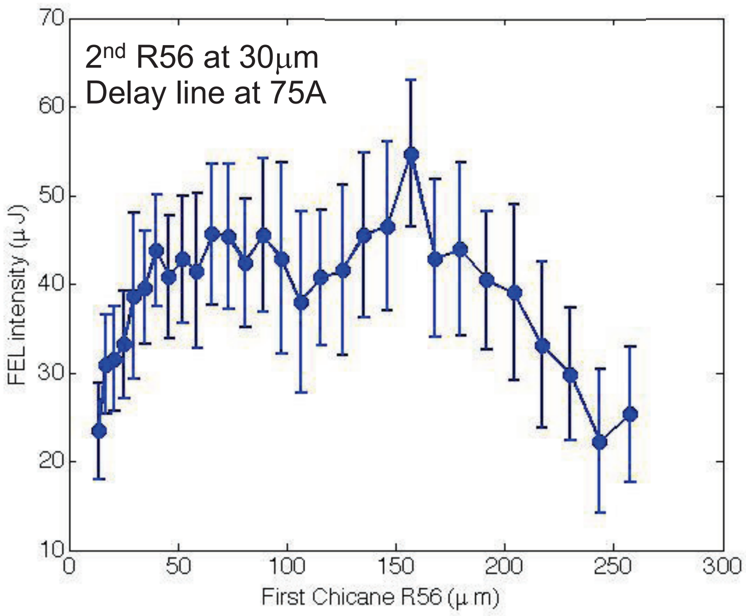

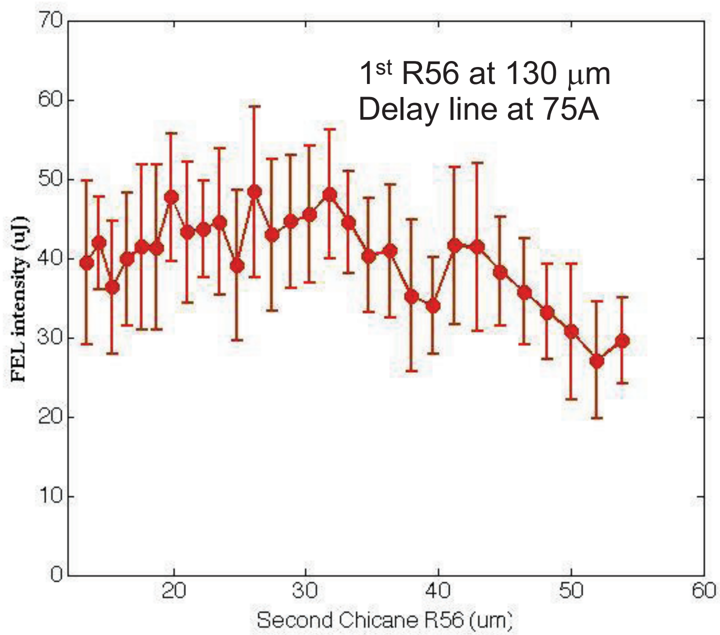

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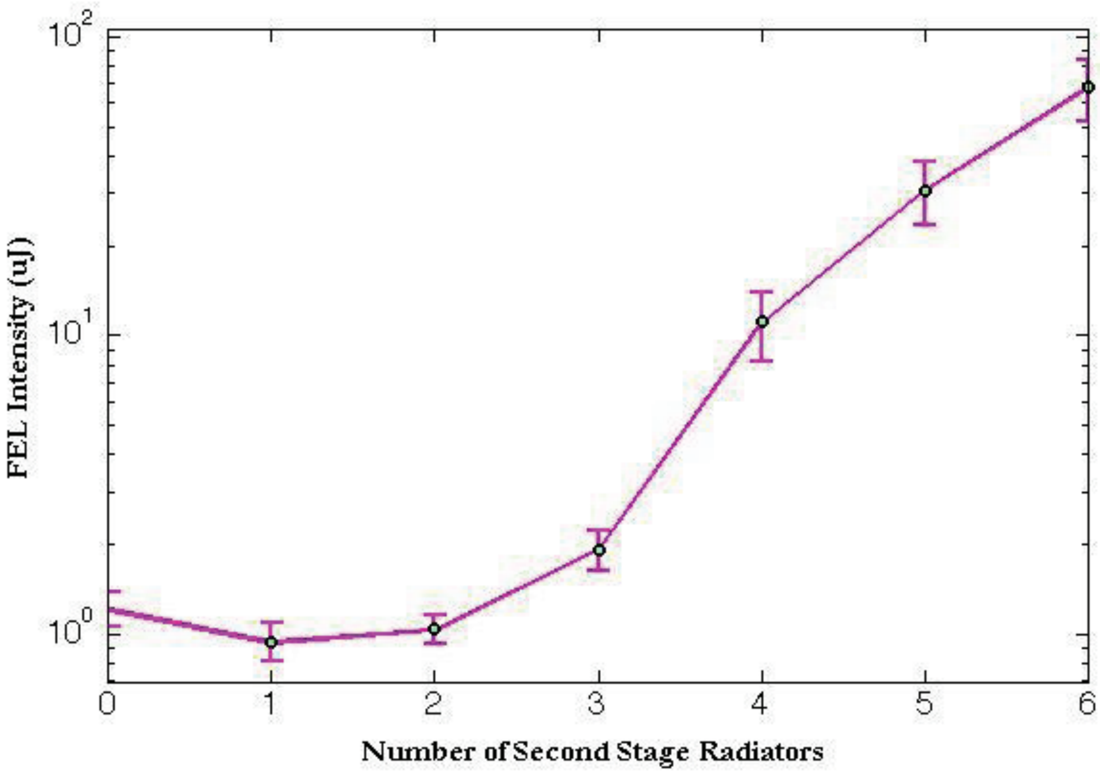
Opt. Kly. Experiment on FEL-2: 12nm

A further improvement of the OK FEL intensity has been obtained by fine tuning the laser heater undulator gap (i.e. beam energy fine tuning at the injector): “big shot” of ~100 μJ



FEL Gain curve measured by closing progressively the second stage radiators.
Gain length ~ 1.37m

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Conclusion

- The optical klystron enhancement to SASE FEL has been experimentally demonstrated at FERMI: down to 20 nm on FEL-1 and at 12 nm on FEL-2.
- Our experiments confirm that the Optical Klystron FEL performance are strongly determined by the beam uncorrelated energy spread.
- 1-D theory can reproduce the experimental observation when microbunching is fully suppressed and the intrinsic energy spread is similar to the "FEL-slice" energy spread.
- Measurements of the OK-FEL gain curve confirm that the gain length is independent on the dispersive section as expected in the simulations.
- FERMI has been able to operate in SASE mode taking advantage of the optical klystorn, providing several tens of μJ in XVUV range..

Thank You

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