Experimental Study of FEL Power Scaling in the Storage Ring FEL

*Presenter : S. Huang**

Y.K. Wu, B. Jia, J. Li, S.F. Mikhailov, V.G. Popov, S. Huang*, W. Z. Wu

DFELL/TUNL, Duke University

***Institute of Heavy Ion Physics, Peking University**

August 24, 2011

Acknowledgment:

M. Busch, M. Emanian, J. Faircloth, G. Swift, P. Wang, P. Wallace

Grant Support: US DOE grant no. DE-FG02-97ER41033

Outline

Motivation to Study Power of Storage Ring FEL (SRFEL)

- Gain new insight into storage ring FEL dynamics
- Predicting Compton gamma-ray flux of the HIGS facility driven by SRFEL

Experimental Study of SRFEL Power vs Operation Parameters

(Average FEL Power is Measured under Routine FEL Operation Conditions)

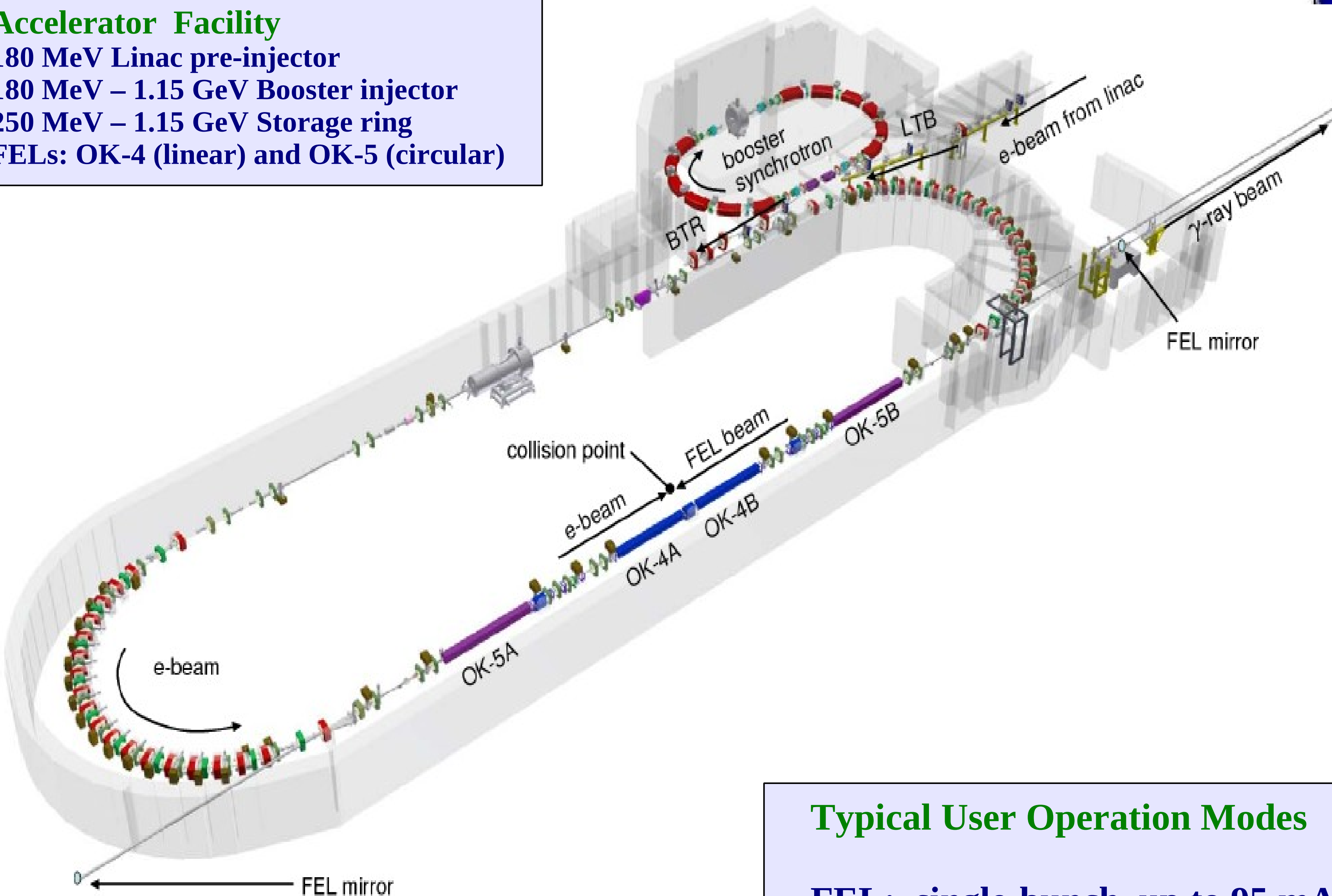
- 1D SRFEL model for FEL power
- Direct and precise measurement of energy spread σ_E using Optical Klystron
- SRFEL power scaling with e-beam energy
- SRFEL power vs e-beam energy and current
- SRFEL power vs FEL detune and RF voltage
- Preliminary result: SRFEL power vs cavity loss
- SRFEL Power Formula

Summary

This work is part of Ph.D. research project of Botao Jia, Duke University (2011).
B. Jia's Ph.D. Dissertation :
"*Study of Storage Ring Free-Electron Laser Using Experimental and Simulation Approaches*"

Duke FEL and High Intensity Gamma-ray Source (HIGS)

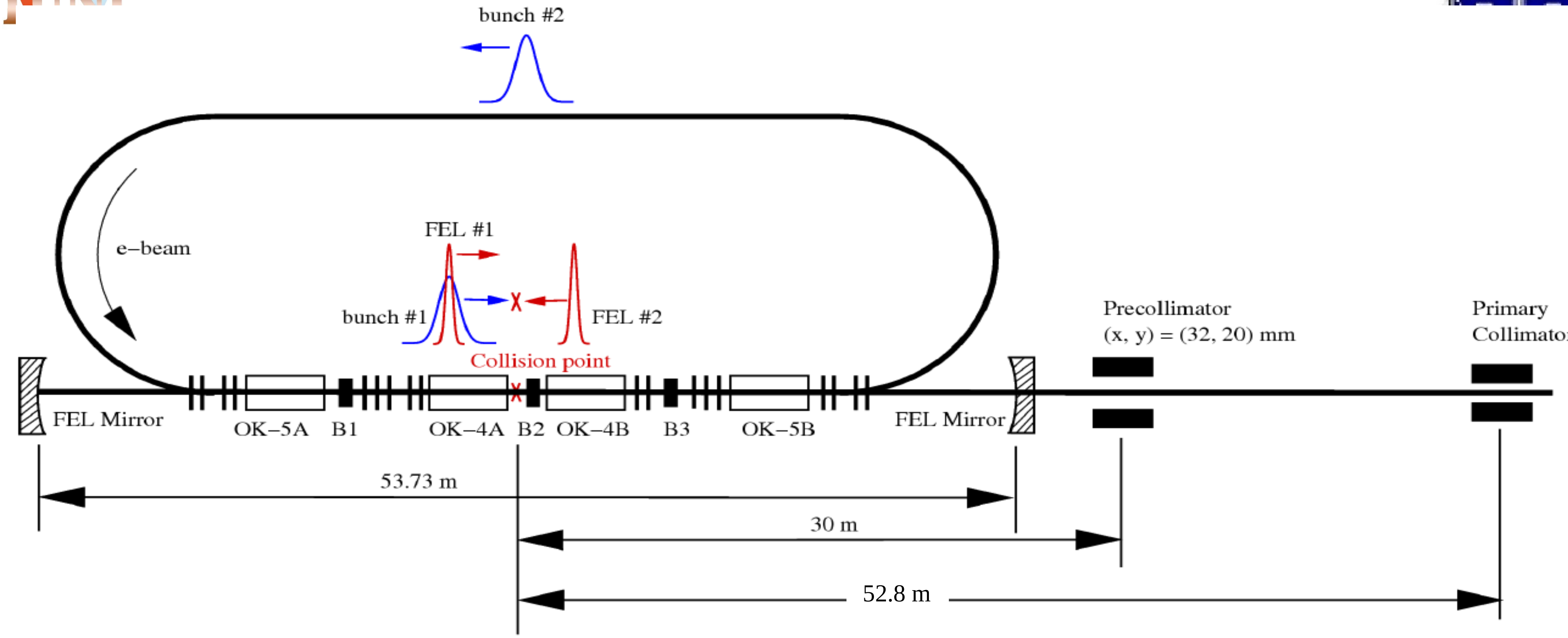
Accelerator Facility
180 MeV Linac pre-injector
180 MeV – 1.15 GeV Booster injector
250 MeV – 1.15 GeV Storage ring
FELs: OK-4 (linear) and OK-5 (circular)

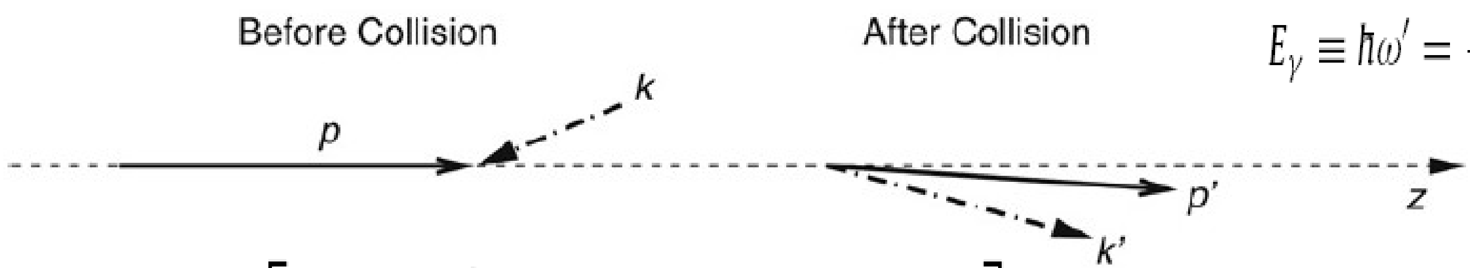


Typical User Operation Modes

FEL: single-bunch, up to 95 mA
HIGS: two-bunch, 80 - 115 mA

Operation Principle of HIGS



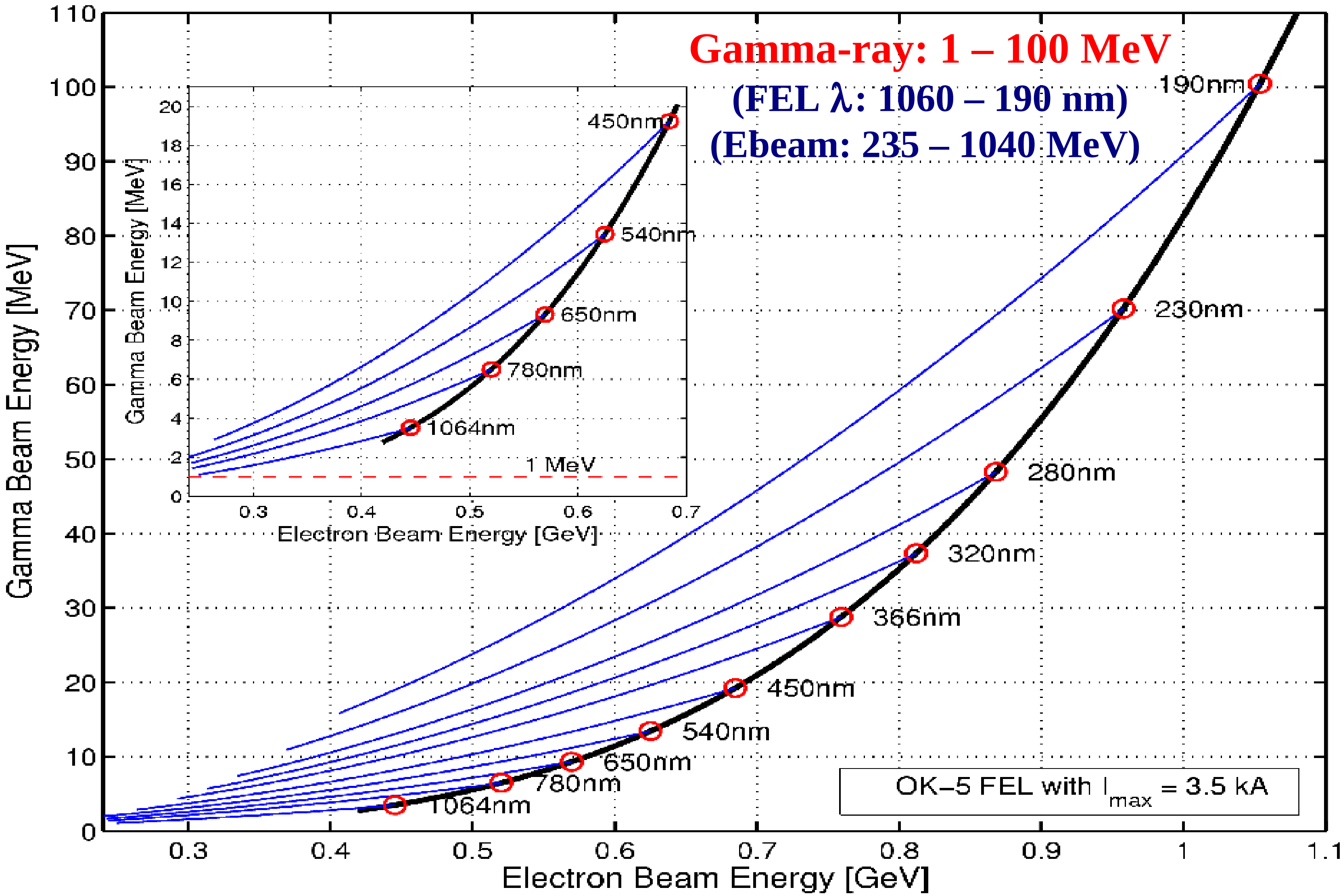


$$E_\gamma \equiv \hbar\omega' = \frac{\hbar\omega(1-\beta\cos\theta_i)}{1-\beta\cos\theta_f + \frac{\hbar\omega}{\mathcal{E}_e}(1-\cos\theta_{ph})}$$

$$d\sigma = 8\pi r_e^2 \frac{dy}{x^2}\left[\left(\frac{1}{x}-\frac{1}{y}\right)^2 + \left(\frac{1}{x}-\frac{1}{y}\right) + \frac{1}{4}\left(\frac{x}{y}+\frac{y}{x}\right)\right]$$

$$x = \frac{2\gamma\hbar\omega(1-\beta\cos\theta_i)}{mc^2}, \qquad y = \frac{2\gamma\hbar\omega'(1-\beta\cos\theta_f)}{mc^2}$$

Gamma Energy Tuning Range with OK-5 FEL



Prediction of gamma-ray flux => Storage ring FEL power

How to predict SRFEL power?

1D SRFEL Model and Limitations, and Proposed Power Formula

1D Fokker-Planck Equation:

$$\frac{\partial f}{\partial t} - b\Omega_s \epsilon \frac{\partial f}{\partial s} + \frac{\Omega_s}{b} s \frac{\partial f}{\partial \epsilon} - \frac{\partial}{\partial \epsilon}\left[a\epsilon f + D_\Sigma \frac{\partial f}{\partial \epsilon}\right] = 0$$

Assumptions:

- Constant diffusion
- Perfect synchronization
- Gaussian distribution in longitudinal space

1. A. Renieri, *IL Nuovo Cimento*, Vol. B3, p.160 (1979)
2. G. Dattoli *et al.*, *Opt. Comm*, Vol. 35, no.3 p407 (1980)
3. *V. N. Litvinenko* , *Ph.D. Thesis*, BINP (1989)
4. S.H. Park, *Ph.D. Thesis*, Duke Univ. (2000)

$$P_{ave} = J_\epsilon P_{SR} \frac{\sigma_E^2 - \sigma_0^2}{\sigma_k} \exp\{-\frac{1}{2}(\sigma_E/\sigma_k)^2\}$$

Realistic FEL Operation Conditions

- Lack of perfect synchronization (detuned)
- Not a perfect Gaussian distribution
- Diffusion is not constant in general

$$P_{FEL}(E, I_b, \sigma_E, \sigma_b, \lambda, \delta f, V_{RF}, cavity-loss, other\ params)$$

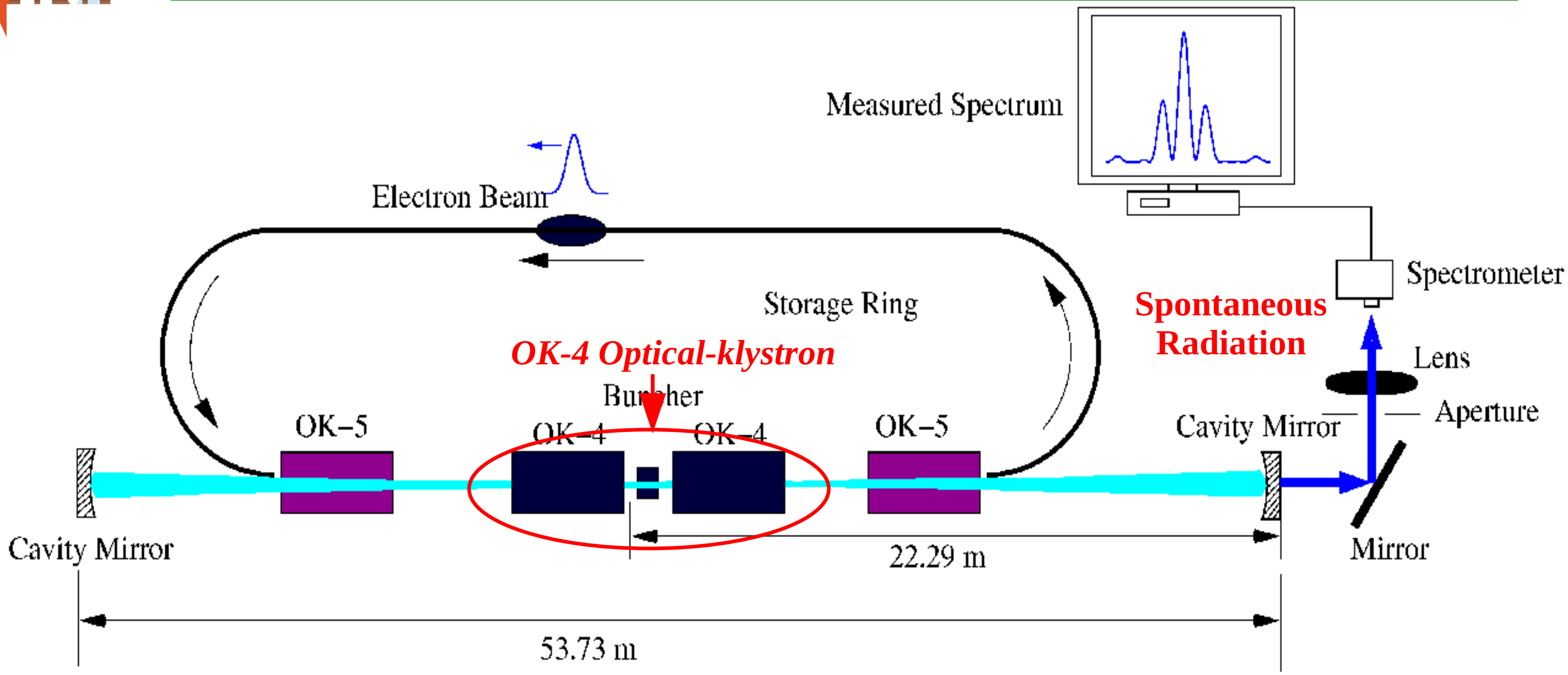
Proposed FEL Power Formula Based Early Works:

Experimental verification needed

$$\Rightarrow \quad P_{FEL} = A I_b E^4 \frac{\sigma_E^2 - \sigma_0^2}{\sigma_E} + B$$

$\Rightarrow$ **Direct and precise measurement of σ_E with or without FEL lasing**

Direct Energy Spread Measurement Using Optical Klystron



$$I_{total}(\lambda) = \int_{-\infty}^{\infty} I_1(\lambda,\gamma)\left[\frac{\sin(\pi N_u(\frac{\lambda_r(\theta=0)}{\lambda}-1))}{\pi N_u(\frac{\lambda_r(\theta=0)}{\lambda}-1)}\right]^2 \times \left\{1+\cos\left[2\pi(N_u+N_d)\frac{\lambda_r(\theta=0)}{\lambda}\right]\right\} f_\gamma(\gamma_0,\sigma_\gamma)d\gamma + h + \xi,$$

$$\lambda_r(\theta) = \frac{\lambda_u}{2\gamma^2}(1+\frac{K_u^2}{2}+\gamma^2\theta^2)$$

$$f_\gamma(\gamma_0,\sigma_\gamma) = \frac{1}{\sqrt{2\pi}\sigma_\gamma}e^{-\frac{(\gamma-\gamma_0)^2}{2\sigma_\gamma^2}}$$

For large energy spread: $\sigma_E > 0.094/N_u$

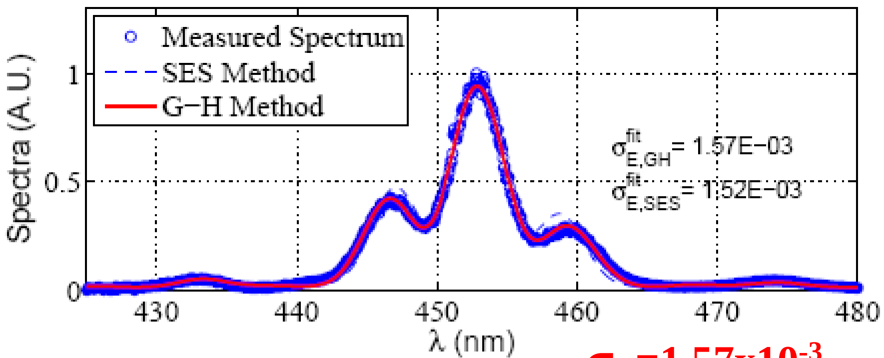
Novel method to precisely determine energy spread

Gauss-Hermite Quadrature Expansion (G-H method)

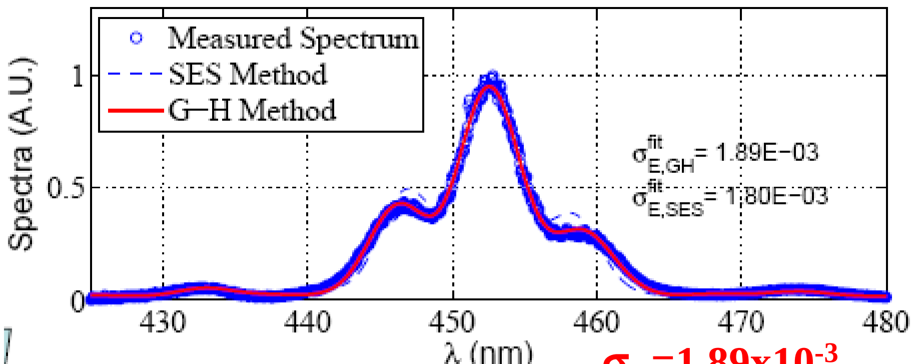
B. Jia *et al.* Phys. Rev. ST Accel. Beams 13, 080702 (2010)

Direct Energy Spread Measurement Using Optical Klystron

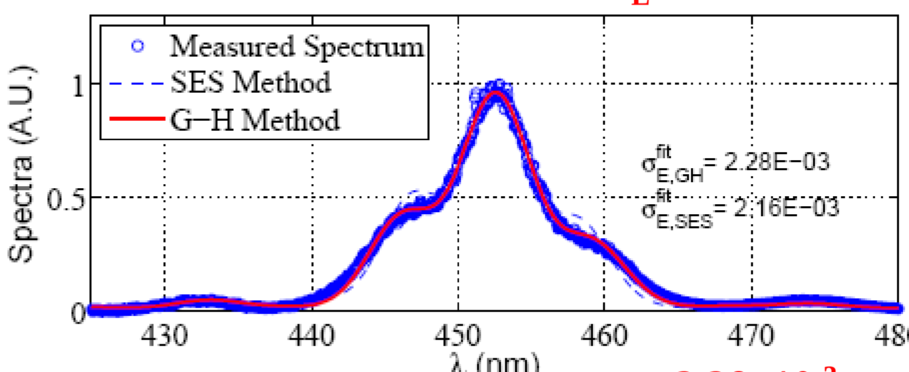
400 MeV, 15 mA (single-bunch), $N_d = 31$



$\sigma_E = 1.57 \times 10^{-3}$



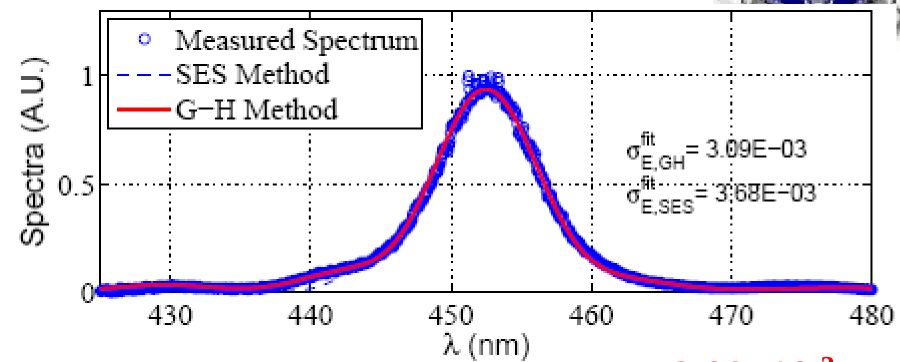
$\sigma_E = 1.89 \times 10^{-3}$



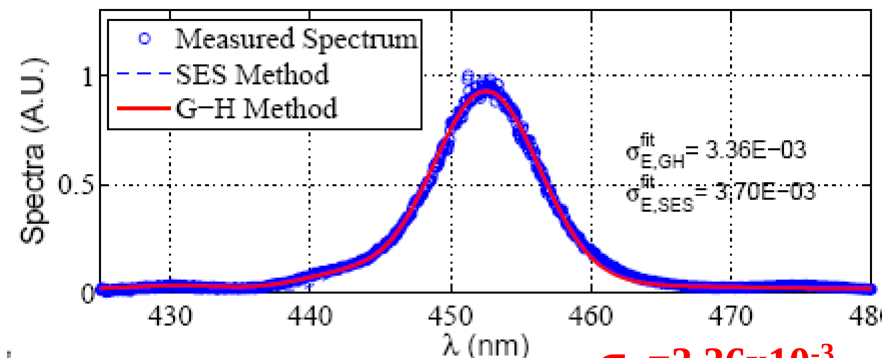
$\sigma_E = 2.28 \times 10^{-3}$

Increase FEL Power

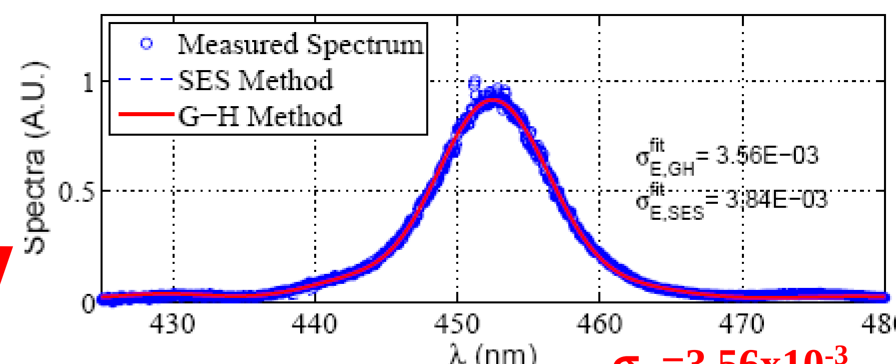
400 MeV, 15 mA, $N_d = 1.09$



$\sigma_E = 3.09 \times 10^{-3}$

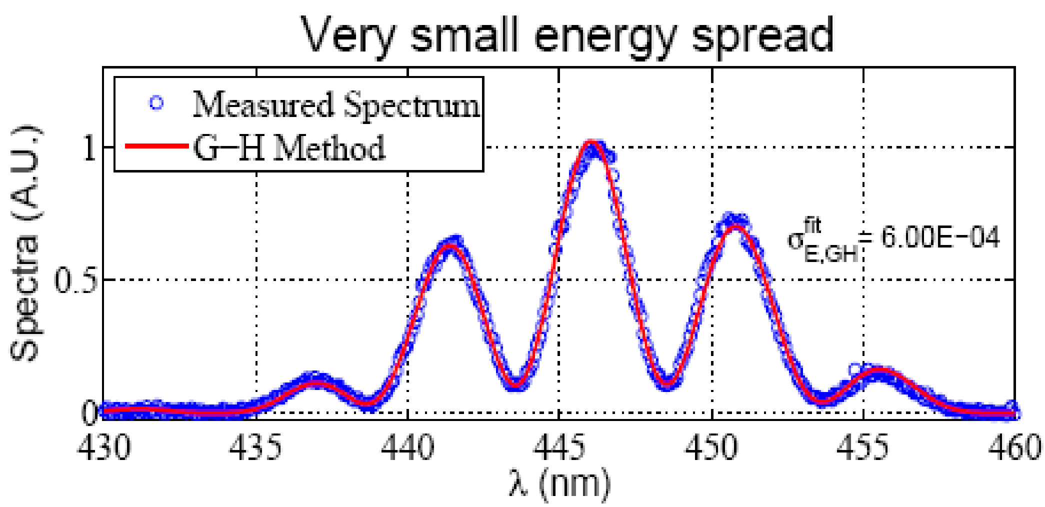


$\sigma_E = 3.36 \times 10^{-3}$



$\sigma_E = 3.56 \times 10^{-3}$

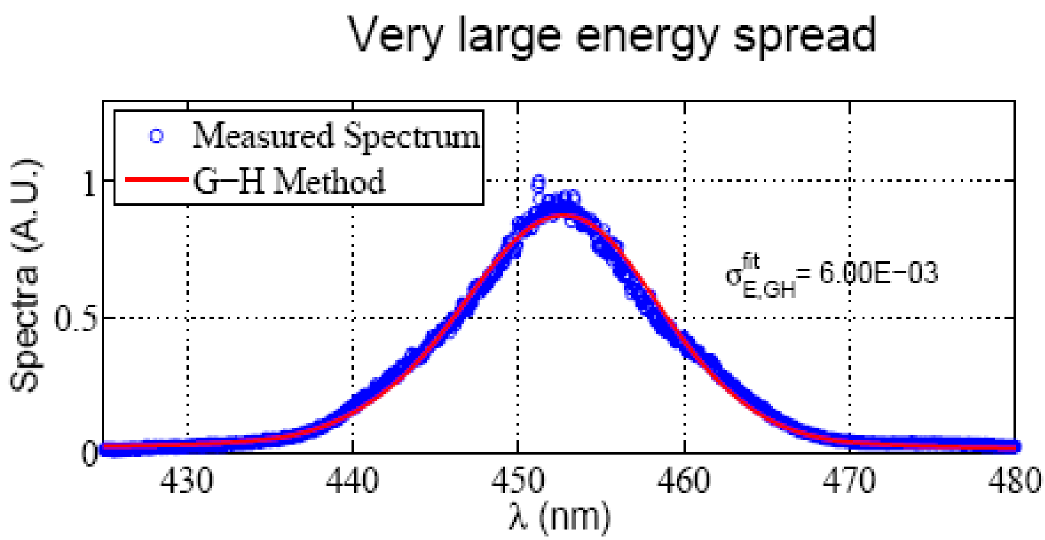
Energy Spread Measurements Extreme Cases



280 MeV, 0.045 mA (single-bunch)

$N_d = 56$

$\sigma_E = 6.00\text{x}10^{-4}$



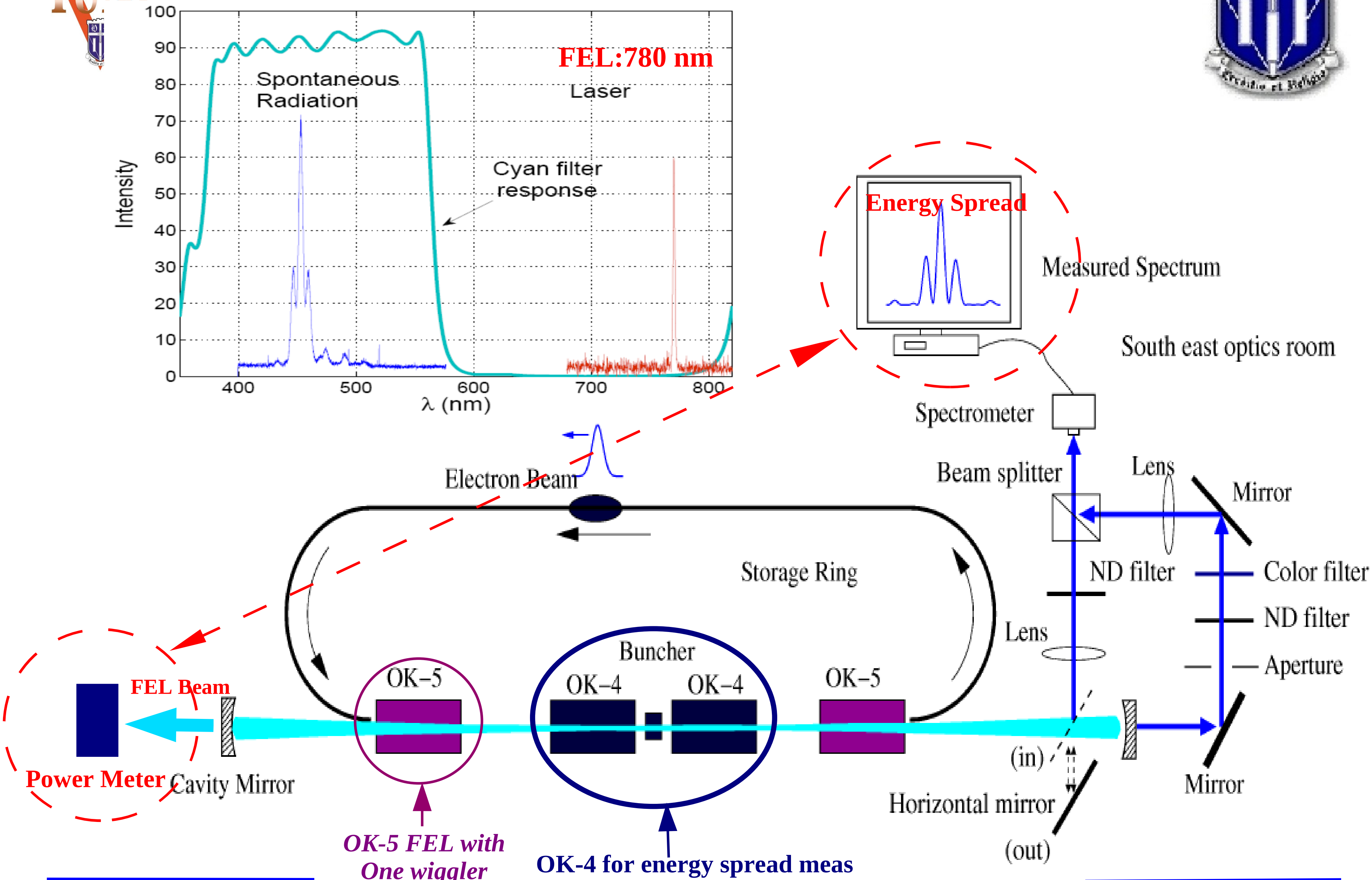
400 MeV, 40 mA with FEL on

$N_d = 1.09$

$\sigma_E = 6.00\text{x}10^{-3}$

Optical Klystron Radiation: Overall accuracy of $\sigma_E \sim 5\%$

Simu. Meas. of FEL and Energy Spread: Two-color Technique



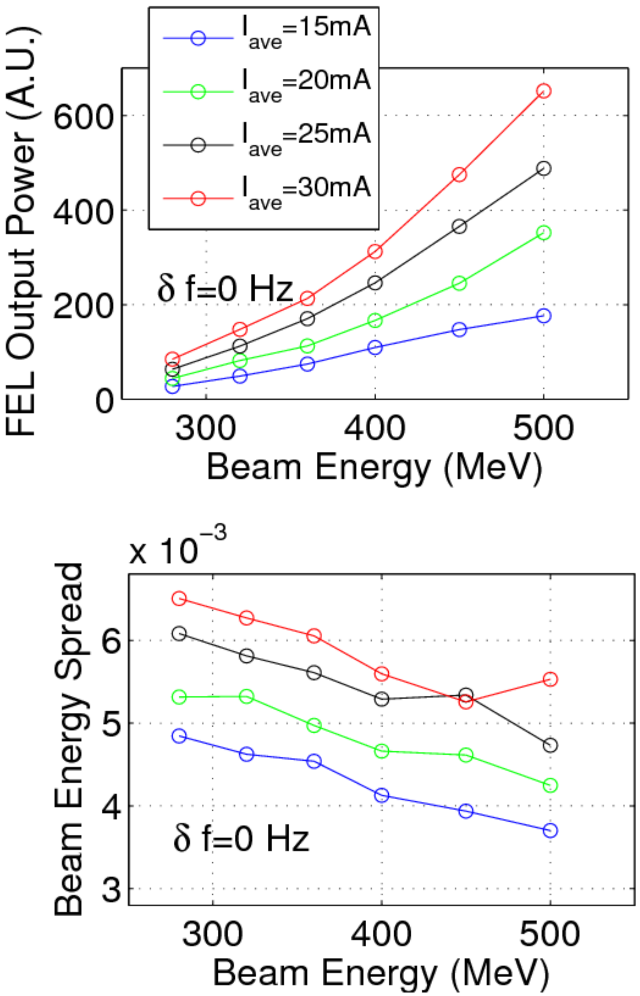
SRFEL Power vs E-beam Energy and Current

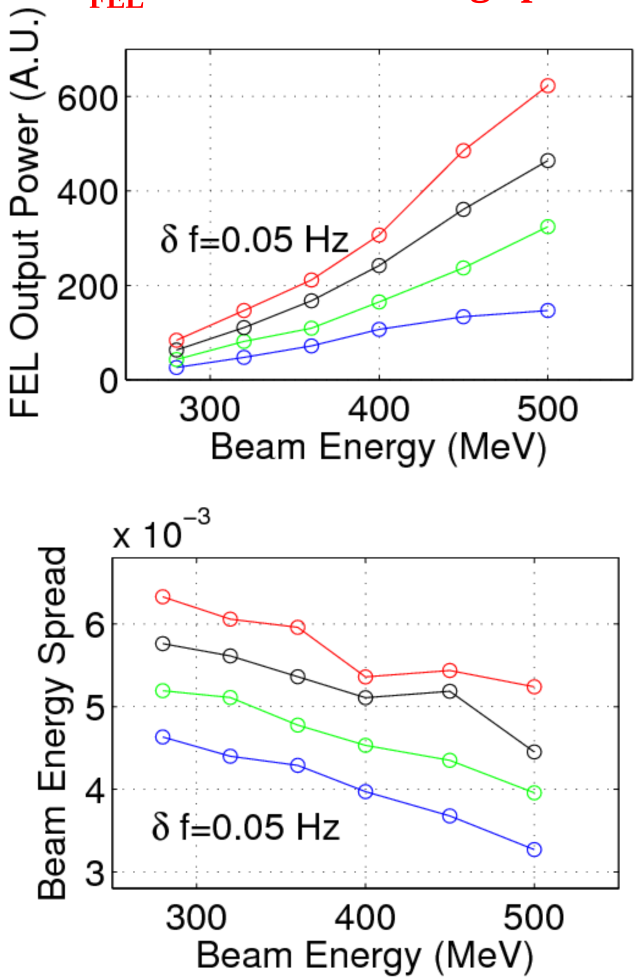
Scanned Parameters:

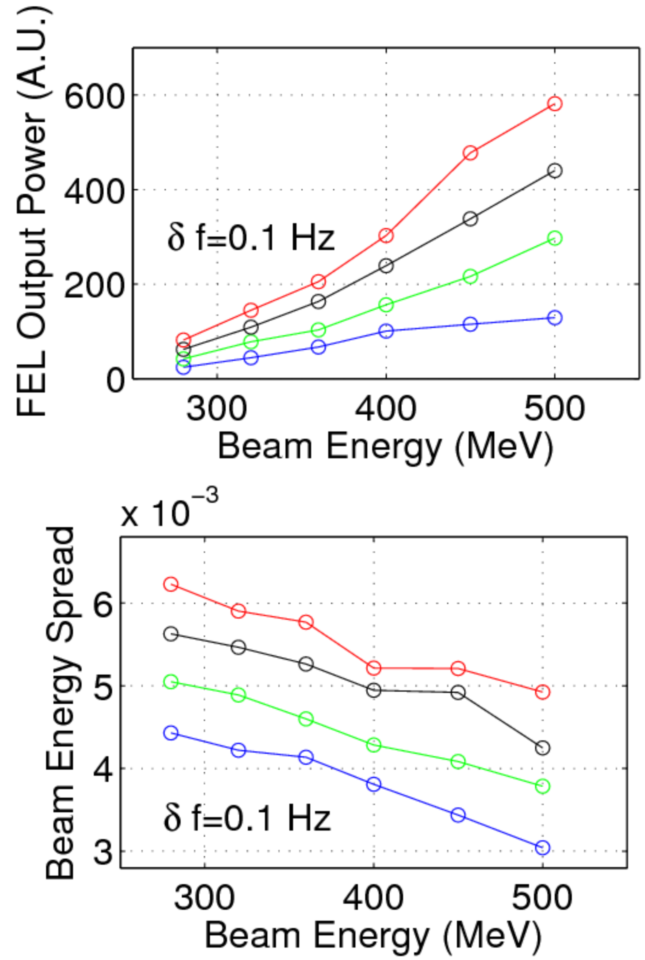
- I_b (single-bunch) varied from 15 to 30 mA
- E varied from 280 to 500 MeV
- Small detune (δf) variations: 0, 0.05, 0.1 Hz (out of 2.79 MHz); Or δ=0, 2, 4 μm

Measured FEL Power:

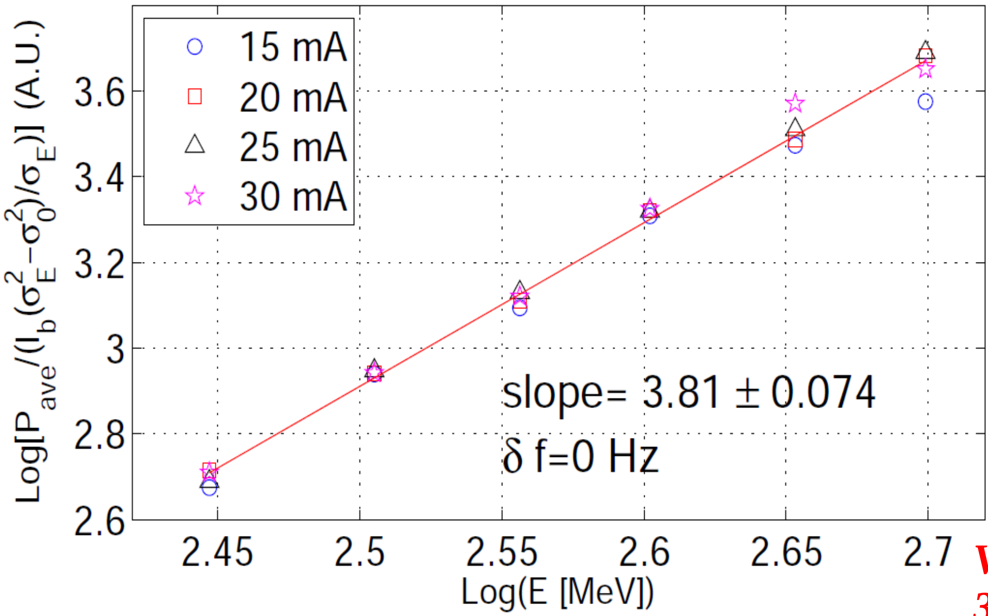
P_{FEL} – extracted average power

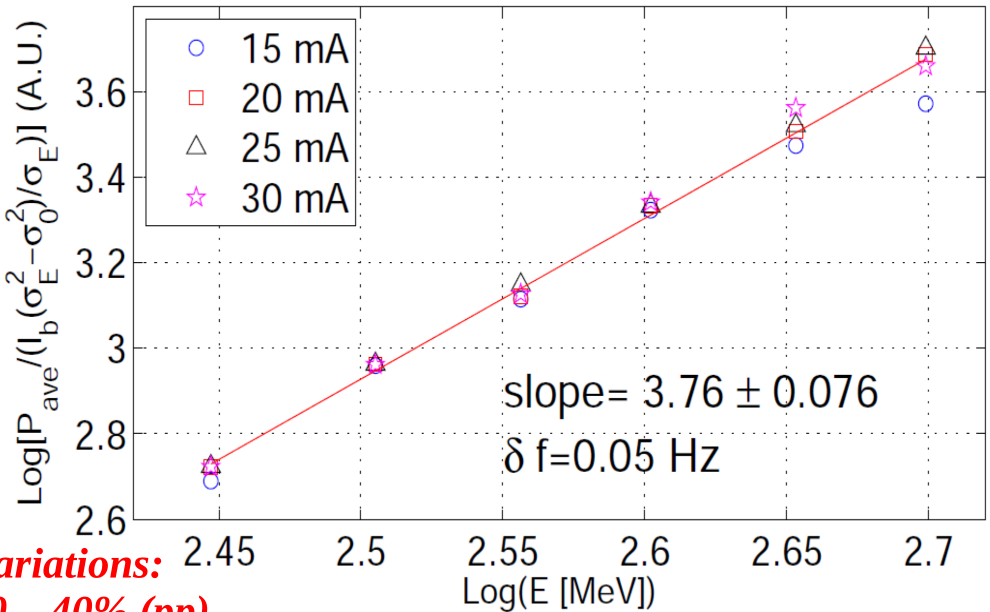




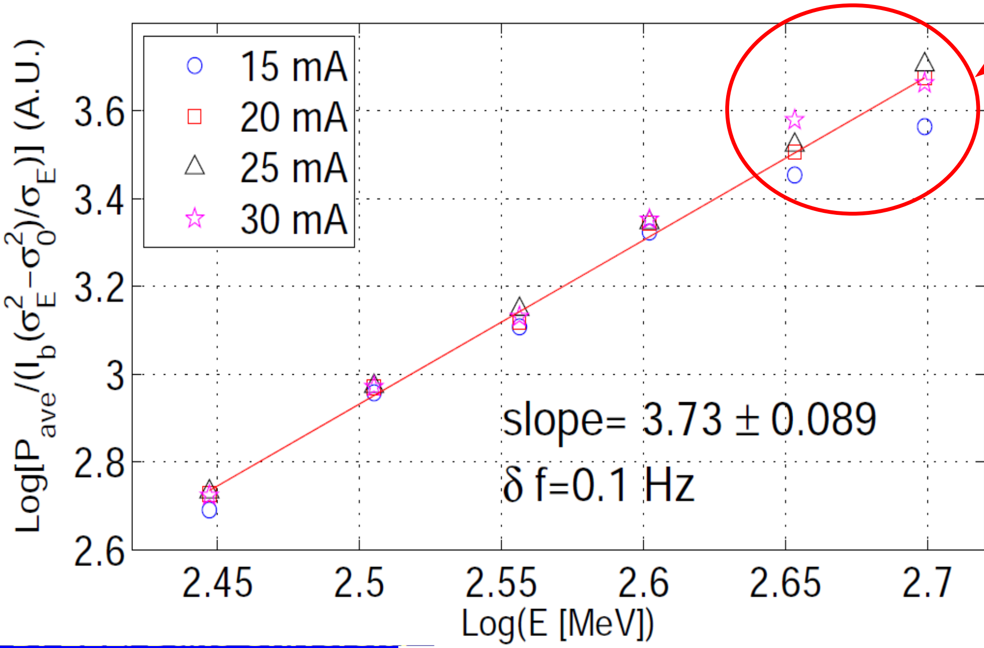


SRFEL Power Scaling with E-beam Energy





Variations: 30 – 40% (pp)

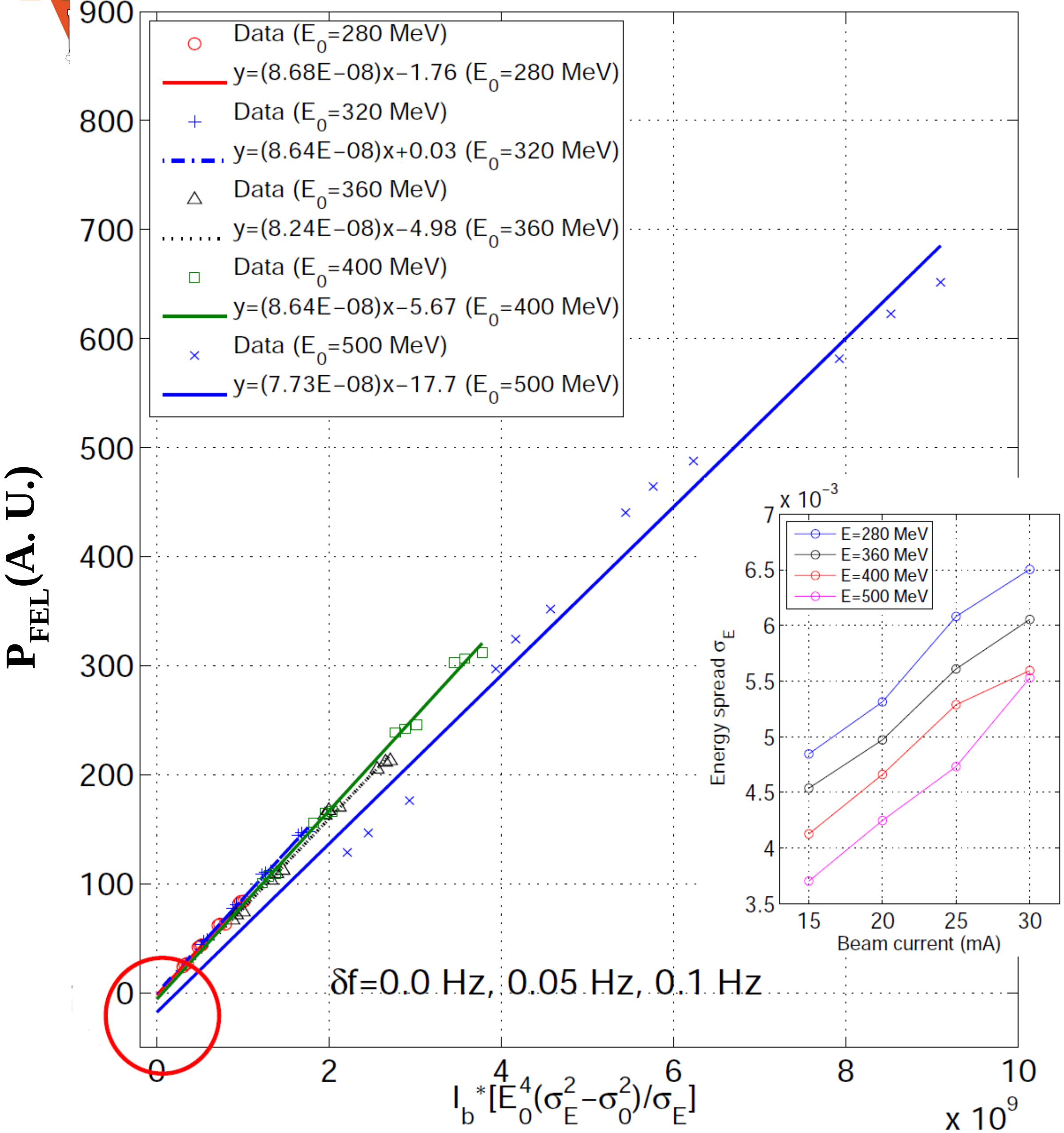


Scaling with E: 4th power expected

$$\log\left(\frac{P_{FEL}}{I_b \dfrac{\sigma_E^2-\sigma_0^2}{\sigma_E}}\right)=\alpha \log(E)$$

α ~ 3.73 – 3.81 (E = 280 – 500 MeV)

SRFEL Power vs Beam Current



$$P_{FEL} \propto \left(E^4\right)\left(I_b \frac{\sigma_E^2(E, I_b) - \sigma_0^2}{\sigma_E(E, I_b)}\right)$$

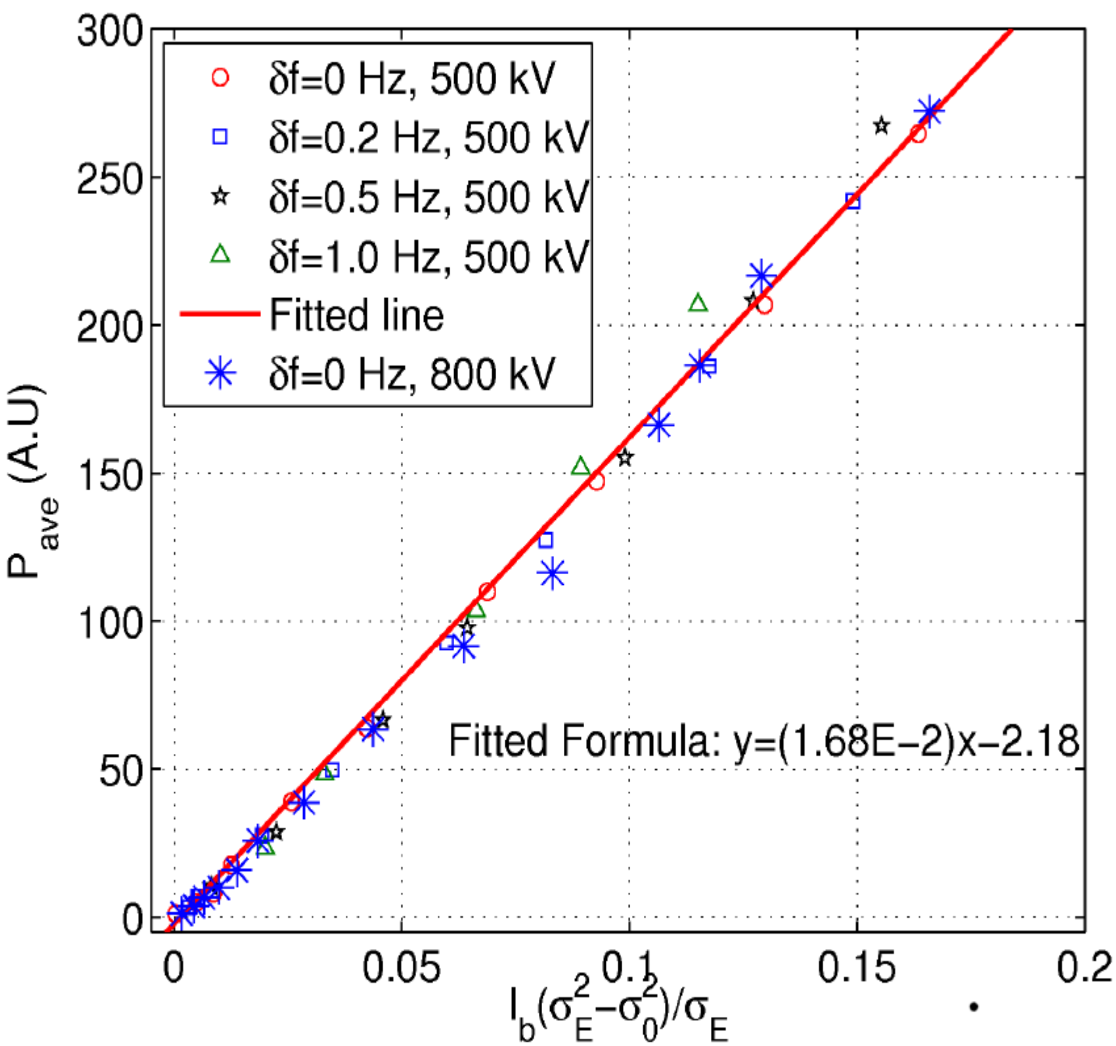
fixed **Linear**

$$P_{FEL} = A\left(E^4\right)\left(I_b \frac{\sigma_E^2 - \sigma_0^2}{\sigma_E}\right) + B$$

A: indep of I_b and E **B: Small**

SRFEL Power vs Detune and RF Voltage

400 MeV, I_b = 4 to 37 mA, V_{RF} (gap)= 500, 800 kV

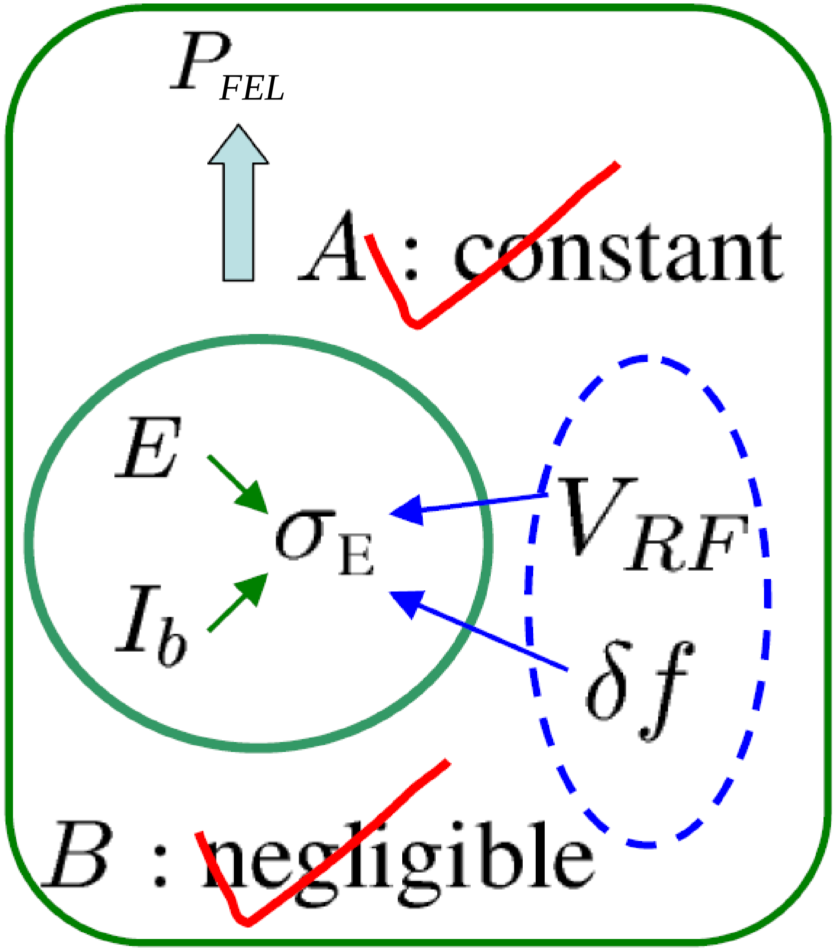


$$P_{FEL} \propto \left(E^4\right)\left(I_b \frac{\sigma_E^2(I_b, \delta f, V_{RF}) - \sigma_0^2}{\sigma_E(I_b, \delta f, V_{RF})}\right)$$

Fixed

Linear

SRFEL Power vs Operation and Beam Parameters



$$P_{FEL} = A\,E^4 \left(I_b \frac{\sigma_E^2(E, I_b, \delta f, V_{RF}) - \sigma_0^2}{\sigma_E(E, I_b, \delta f, V_{RF})} \right) + B$$

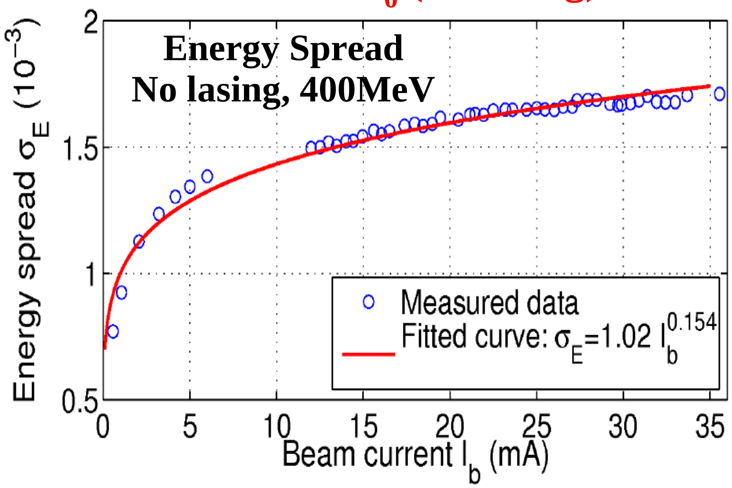
Constant (A) — Neglegible (B)

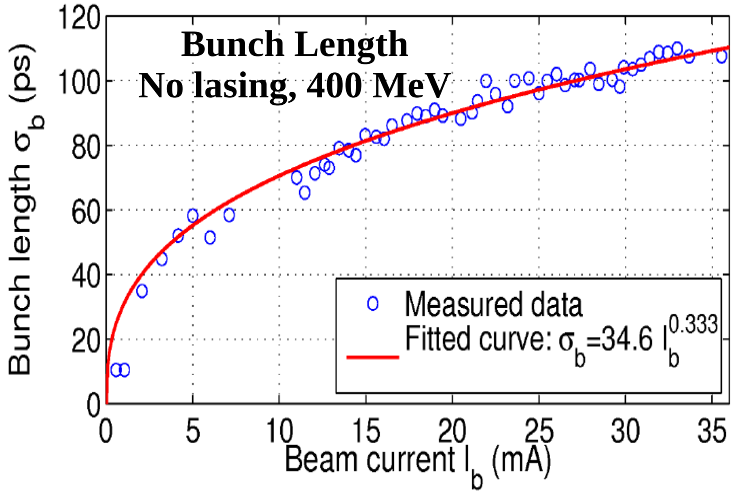
Coef A

- Determined experimentally
- For intracavity FEL power, using measured gamma-ray flux

Predicting SR FEL Power Using Bunch Length

Measured σ_0 (no lasing)



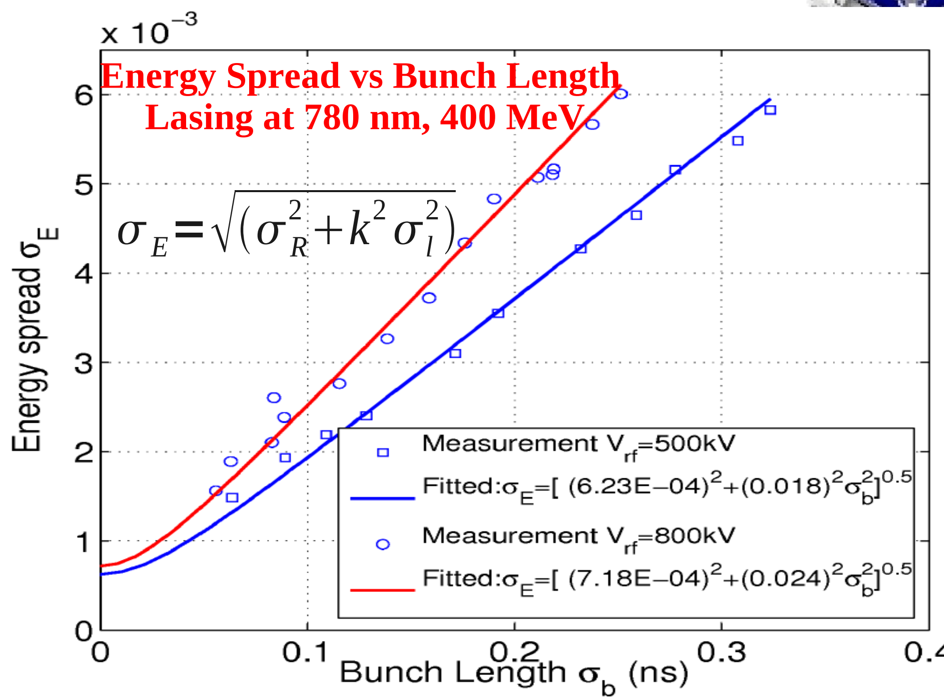


Longitudinal Dynamics

Not a simple rotation in

Microwave instability region

$$\frac{\sigma_E}{\sigma_l} \neq \frac{\Omega_s}{\alpha_c c} = k$$



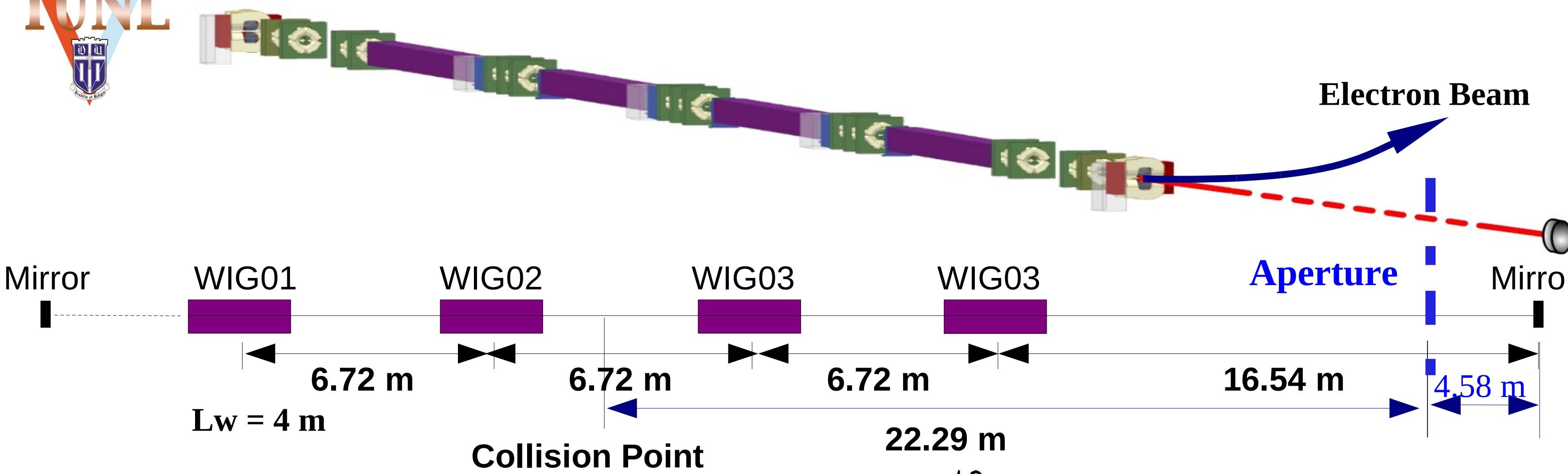
FEL On

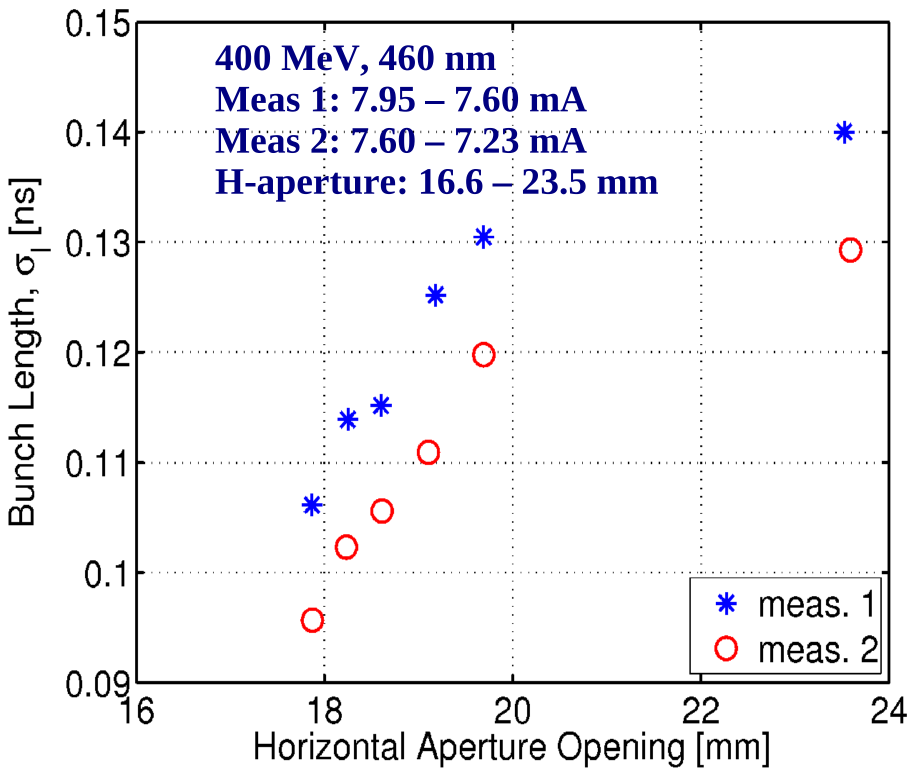
$$\sigma_E \rightarrow \sigma_l$$

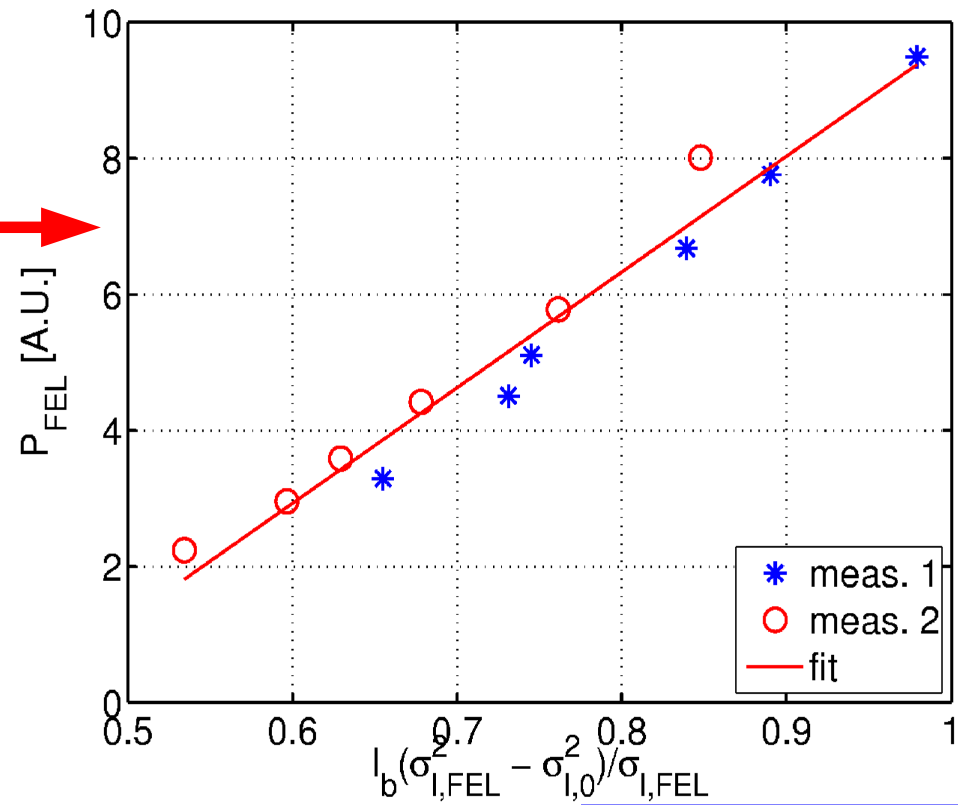
$$\sigma_E = \sqrt{\sigma_R^2 + k^2 \sigma_l^2}$$

$$P_{FEL} = f(E, I_b, \sigma_l; \sigma_0)$$

Preliminary Result: SRFEL Power vs Cavity Loss







Summary

New Analysis Method to Enable Precise Meas. of σ_E Using Optical Klystron

- For a large range of σ_E (few 10^{-4} to few 10^{-3})
- Overall accuracy: 5%

Systematic Study of SRFEL Power Dependency on Operation Parameters

Direct dependency

$P_{FEL} = f(E, I_b, \sigma_E; \sigma_0)$

$\sigma_E(E, I_b, ...)$

Indirect dependency

$P_{FEL} = f(E, I_b, \sigma_E; \sigma_0)$

$\sigma_E(\delta f, V_{RF}, \text{cavity-loss}, ...)$

SRFEL Power Formula (avg, steady state)

$$P_{FEL} = A E^4 I_b \frac{\sigma_E^2 - \sigma_0^2}{\sigma_E} \qquad A = const$$

Good within +/- 10% to +/-20% for Duke SRFEL (280 – 500 MeV, 4 – 40 mA)

Adequate for predicting gamma-ray flux