Transverse Gradient Undulator to Enhance the FEL Performance for a Laser Plasma Accelerator

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SLAC NATIONAL ACCELERATOR LABORATORY

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LPA beam parameters achievable today

- Energy: ~ 100 MeV - 1 GeV
  - Obtained with 10-100 TW laser pulses in mm - cm long plasmas
- Charge: ~ 1- 100 pC
  - Depends on tuning, energy spread due to beam loading
- Energy spread: ~ 1 - 10% level
  - Depends on amount of charge, trapping physics
- Normalized Emittance: ~ 0.1 micron
  - Based on divergence measurements (~ 1 mrad) and e-beam spot (~0.1 micron)
  - Improved measurements needed
- Bunch duration: ~ 1 - 10 fs
  - Based on optical probe, CTR, and THz measurements
- Rep. rate (laser system): 1 - 10 Hz
  - limited by availability of high average power lasers
- Foot-print (laser system): ~ (few meter) x (few meter)

Driver for GeV Laser Plasma Accelerator:
commercial 30 W-average (10 Hz), 100 TW-peak laser system

C. Schroeder, FLS2012

LPA 6D beam brightness comparable to conventional sources

$$B_{6D} = \frac{N}{\epsilon_{nx}\epsilon_{ny}\epsilon_{nz}} \approx \frac{(I/I_A)}{r_e \epsilon_n^2 \sigma_\gamma} = b_6 \lambda_c^{-3}$$

LPA

ε_N = 0.1 micron
0.5 GeV
4% energy spread
I = 3 kA (~5 fs)

$b_6 \sim 9 \times 10^{-12}$

LCLS

ε_N = 0.4 micron
13.6 GeV
0.01% energy spread
I = 3 kA

$b_6 \sim 9 \times 10^{-12}$

- Energy spread order of magnitude too large (for soft-x-ray FEL; ρ ~ few $\times 10^{-3}$)
- Bunch duration < slippage length (for soft x-ray FEL)
- Emittance exchange?

C. Schroeder, FLS2012

Reducing the sensitivity of a free-electron laser to electron energy

T. I. Smith, J. M. J. Madey, L. R. Elias, and D. A. G. Deacon

Department of Physics and High Energy Physics Laboratory, Stanford University, Stanford, California 94305

(Received 6 November 1978; accepted for publication 14 February 1979)

J. App. Phys. **50**, 4580 (1979)

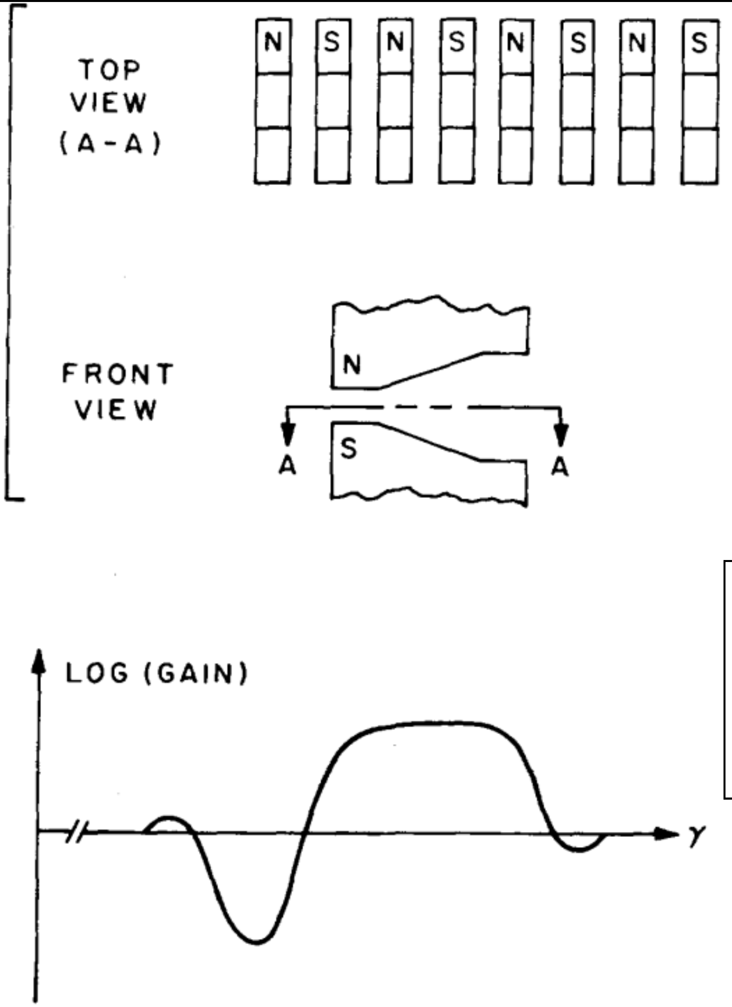


FIG. 3. This magnet is designed to provide constant gain for the electrons injected near the center of the magnet with the normal dependence of gain on energy outside the center.

- Considered low-gain FEL only
- Several follow-up papers but no actual device based on it

IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. QE-17, NO. 8, AUGUST 1981

Theory of the Transverse Gradient Wiggler

NORMAN M. KROLL, PHILLIP L. MORTON, MARSHALL N. ROSENBLUTH, JAMES N. ECKSTEIN, AND JOHN M. J. MADEY

Transverse Gradient Undulator (TGU)

- FEL resonant condition

$$\lambda_r = \frac{\lambda_u}{2\gamma_0^2}\left(1 + \frac{K_0^2}{2}\right)$$

- By canting the undulator poles, generate a linear field gradient

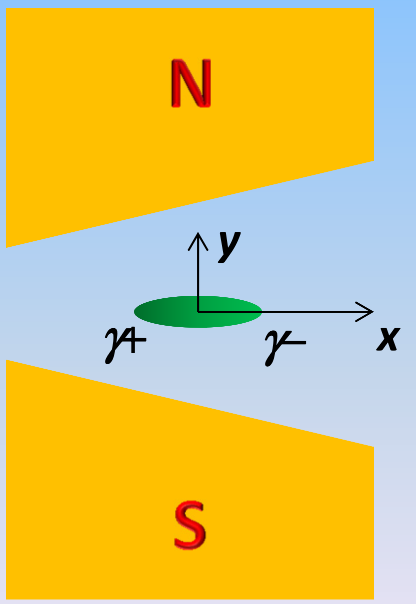
$$\frac{\Delta K}{K_0} = \alpha x$$

- Sort e-beam energy by dispersion η so that

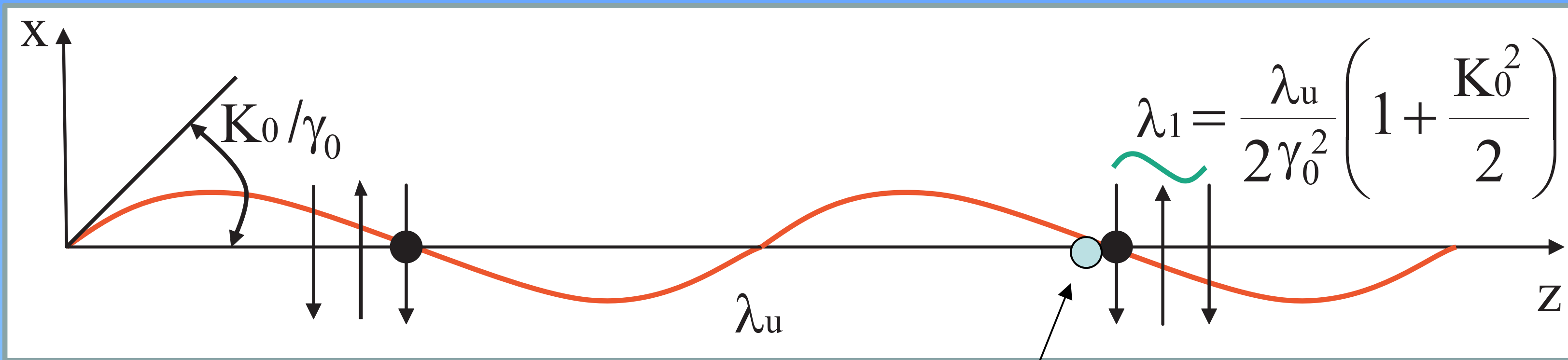
$$x = \eta\frac{\Delta\gamma}{\gamma_0}$$

- Resonance can be satisfied for all energies if

$$\eta = \frac{2 + K_0^2}{\alpha K_0^2}$$



Effects of Energy Spread



off-energy particle

➢ For efficient FEL interaction, the resonant wavelength spread caused by the energy spread over a gain length << 1

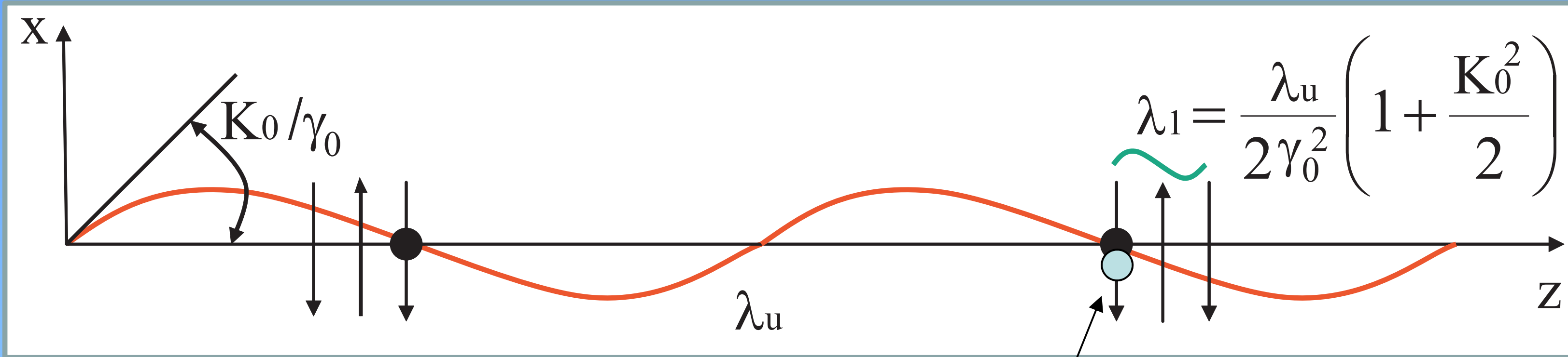
$$\frac{\Delta\gamma}{\gamma} = \frac{\Delta\lambda}{2\lambda_r} << \frac{\lambda_u}{2L_G} \approx 4\pi\rho$$

➔ $\sigma_\delta << \rho \sim 10^{-3}$ for short-wavelength FELs

➢ This is a local energy spread requirement not projected (for LPAs, bunch length ~ slippage, local ~ projected)

➢ TGU compensates this effect with $K(x)/\gamma(x)$

Effects of Energy Spread



off-energy particle in TGU

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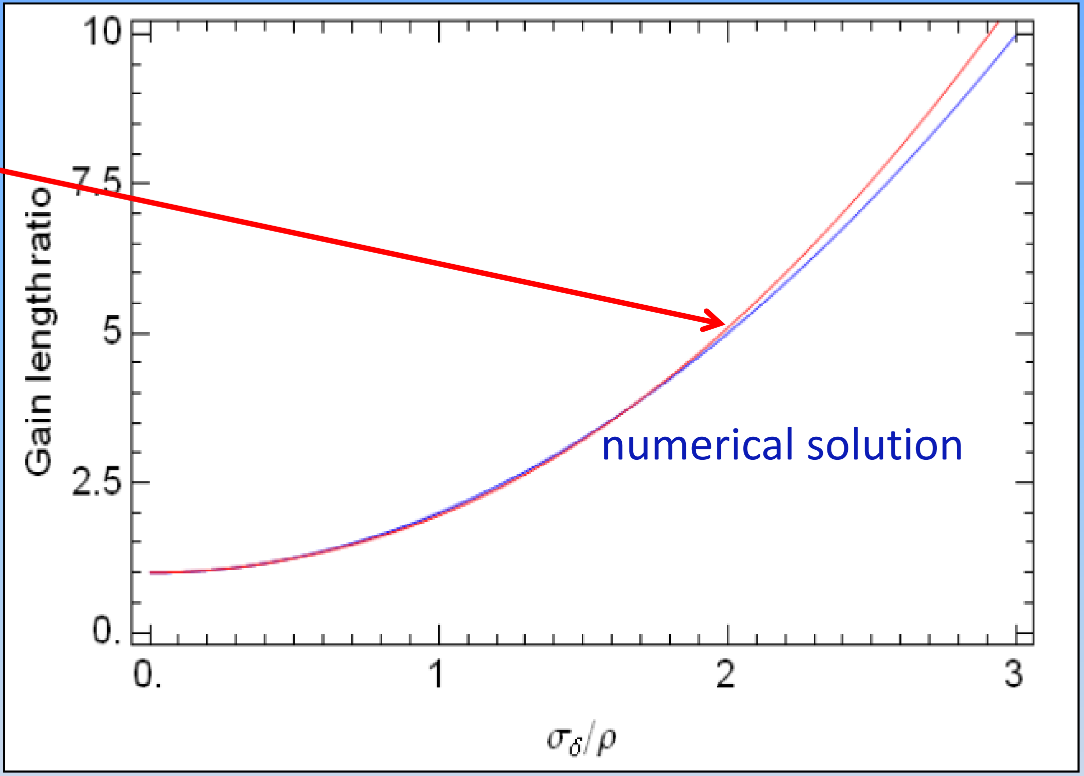
- TGU compensates this effect with $K(x)/\gamma(x)$

1D FEL analysis

- Effects of energy spread on gain length can be estimated as

$$L_G \approx \frac{\lambda_u}{4\pi\sqrt{3}\rho}\left(1+\frac{\sigma_\delta^2}{\rho^2}\right)$$

Gain length ratio = $\dfrac{L_G}{\lambda_u/(4\pi\sqrt{3}\rho)}$



- High-gain FEL requires a beam with small E-spread

$$\sigma_\delta = \frac{\sigma_\gamma}{\gamma_0} \ll \rho$$

Gain Enhancement in TGU

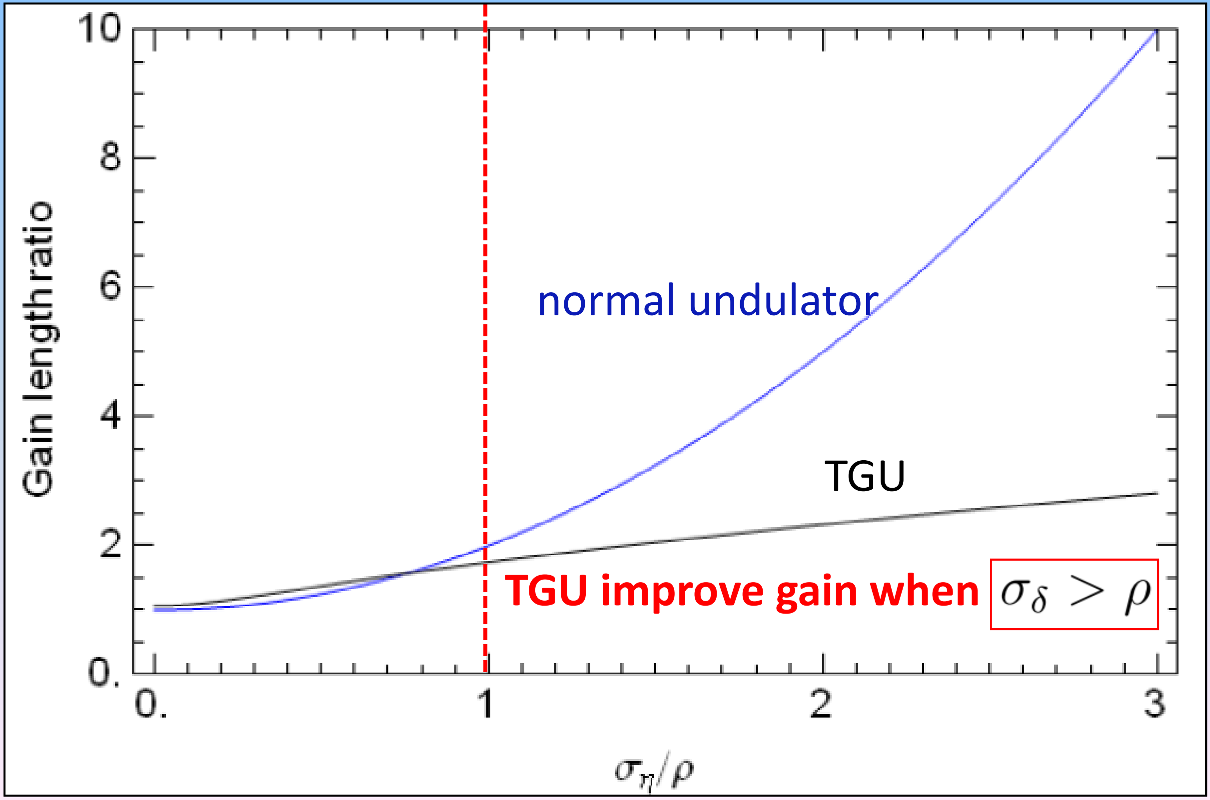
- Trade energy spread with horizontal beam size

effective FEL paramater

$$\rho_T = \rho \left(1 + \frac{\eta^2 \sigma_\delta^2}{\sigma_x^2}\right)^{-1/6}$$

$$L_G^T \approx \frac{\lambda_u}{4\pi\sqrt{3}\rho_T}\left[1 + \left(\frac{K_0^2}{2+K_0^2}\right)^2 \frac{\alpha^2 \varepsilon_x L_u}{2\rho_T^2}\right]$$

Emittance matters here!



TGU improve gain when $\sigma_\delta > \rho$

Comparison with Decompression

- Decompression reduces (slice) energy spread with corresponding reduction in peak current, and can enhance FEL gain similar to TGU (e. g., A. Maier *et al.*, submitted; A. Loulergue *et al.*, **WEPD05**; C. Schroeder *et al.*, **THPD57**)

- But TGU has the following advantages
  - **Shorter** x-ray pulse length and **higher** peak x-ray power;
  - **Smaller** radiation bandwidth;
  - **Enable seeding** by reducing effects of large energy spread.
  - **Stable** central wavelength in presence of energy jitters

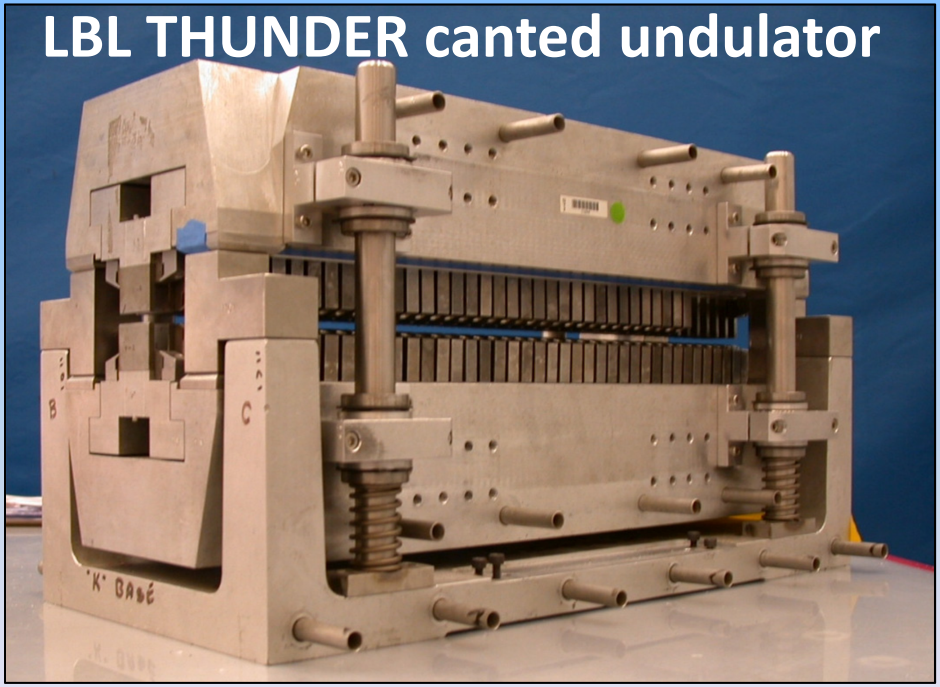
- Depending on beam parameters (bunch length,…), may want to **combine** TGU with decompression technique

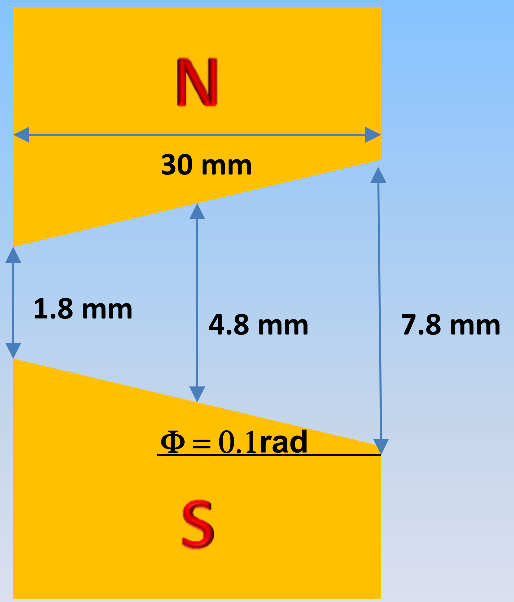
Transverse gradient strength

- Hybrid undulator, use Halbach formula

For a full undulator cant angle $2\phi \approx \Delta y/(\Delta x)$,

$$\alpha = 2\phi \frac{1}{K_0}\frac{\partial K_0}{\partial y} = 2\phi\left(\frac{5.47}{\lambda_u} - 3.6\frac{g}{\lambda_u^2}\right)$$





K. Robinson et. al, PAC1987 and IEEE J. Quan. Electronics, 1987

e.g., $2\phi = 0.2$ rad, $\lambda_u = 2.18$ cm, g = 4.8 mm → **$\kappa = 43\ m^{-1}$**

Superconducting TGU

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A novel undulator concept for electron beams with a large energy spread

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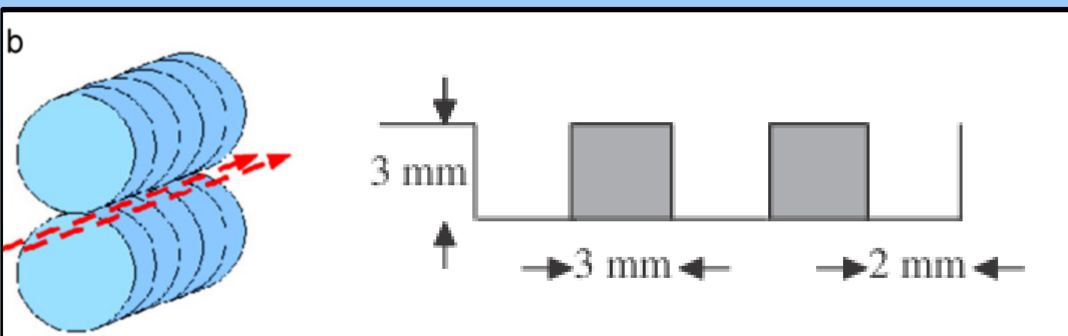


Period length	λ_u	10 mm
Width of the groove	d_{groove}	3 mm
Pole width	d_{pole}	2 mm
Depth of the groove	h_{groove}	3 mm
Minimum gap	h_{gap}	1 mm
Min. bending radius	r_b	1 cm
Number of periods	N	100

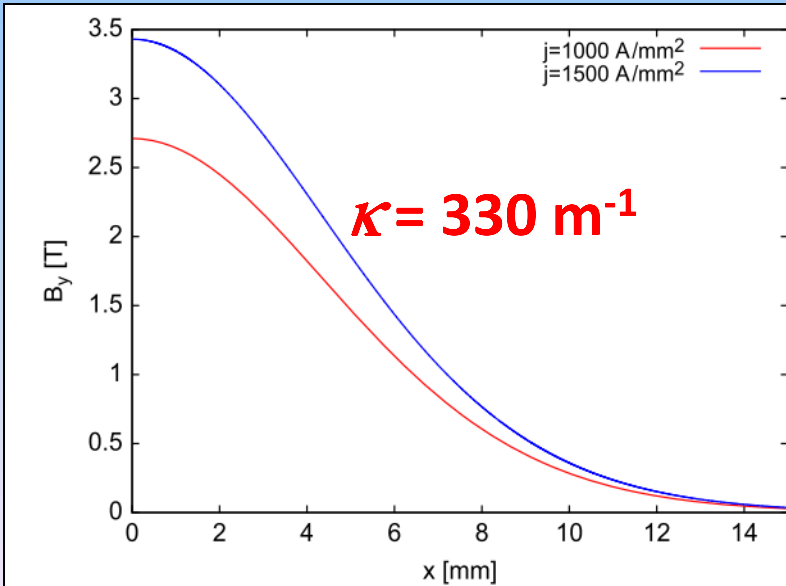


Fig. 5. $B_y(x)$ for the assumed undulators.

3D Effects

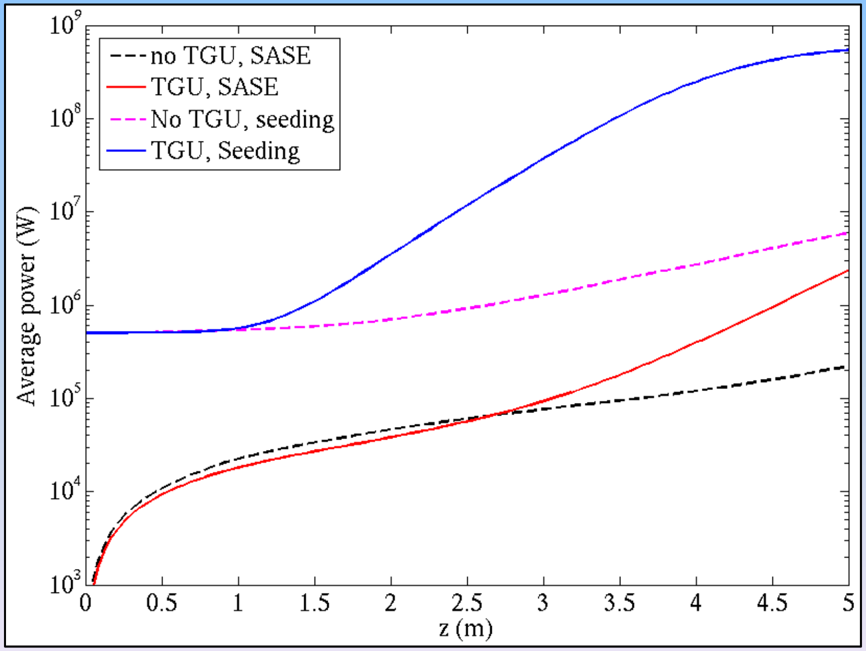
- A net bending field as electrons see a stronger B in one half of the undulator period than the other. Equivalent dipole field

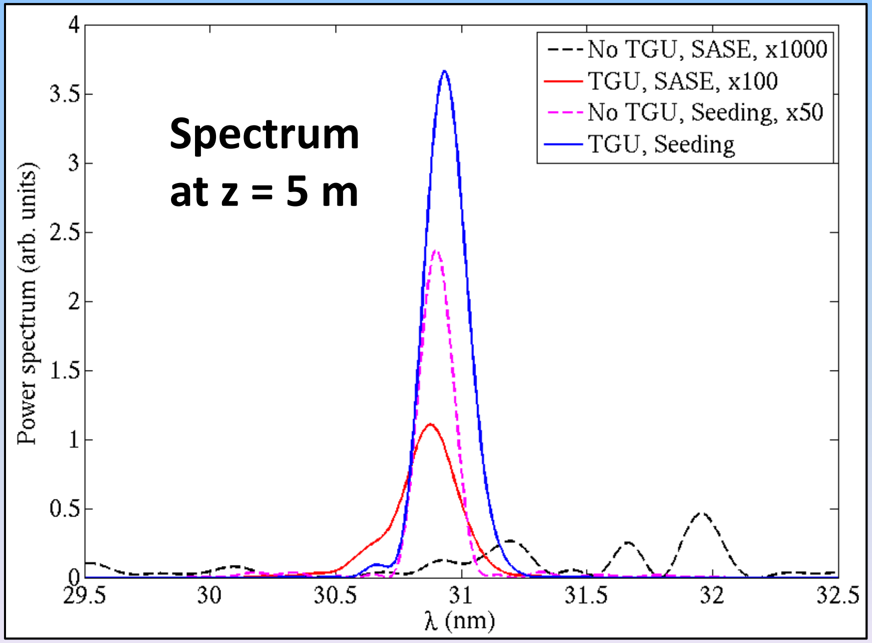
$$\frac{\partial B_u}{\partial x}\frac{K_0}{\gamma_0 k_u} = \frac{K_0^2 mc\alpha}{\gamma_0}$$

  a weak field (a few Gauss for GeV bean) and is correctable
- TGU gives rise to x-focusing (negligible for a short undulator of ~5m, will require attention for a longer undulator)
- Flat beam generates multiple horizontal modes
  ➔ lower effective peak current for each mode,
  ➔ Results in some loss of gain (still significant improvement)
- Use seeding and/or stronger TGU (hence less flat beam) to enhance transverse coherence

LBNL THUNDER as a TGU example

- 500MeV beam with 2% energy spread (rms)
- 5kA, 0.1um emittance, 10 fs (50 pC);
- 5-m undulator, $\lambda_u = 2.14$ cm, $a_u = 1.31$, $\kappa = 43\ m^{-1}$;
- Radiation wavelength $\lambda_1 = 31$ nm
- For TGU, dispersion $\eta = 3.7$ cm, trans. e-beam size: 790umx20um

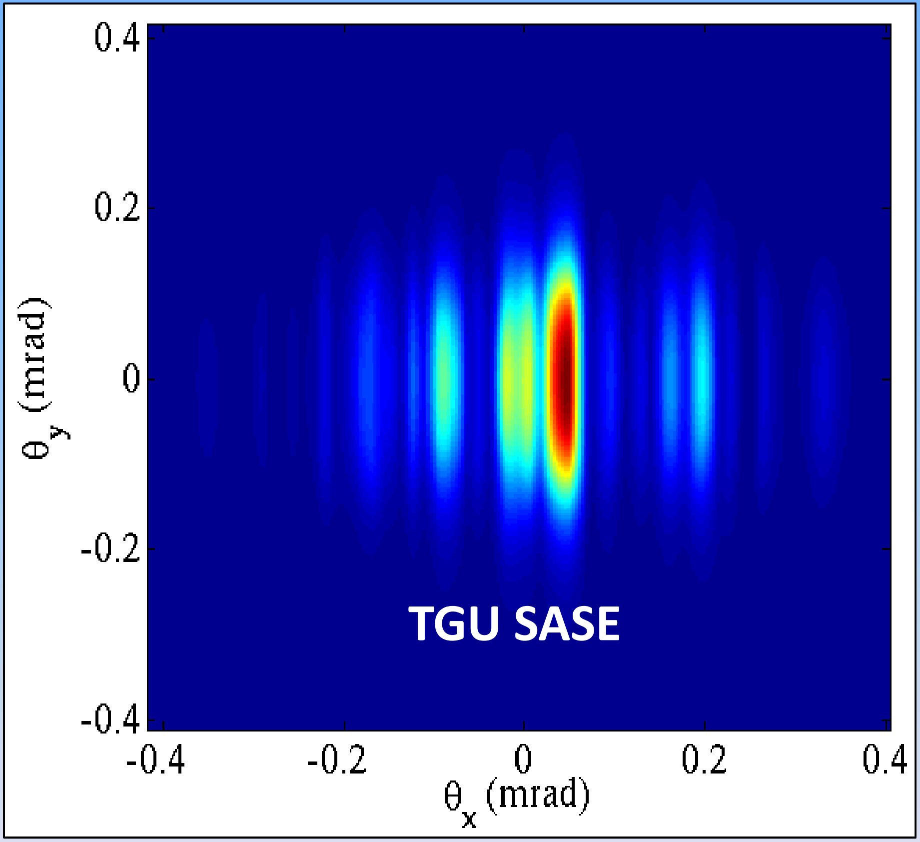


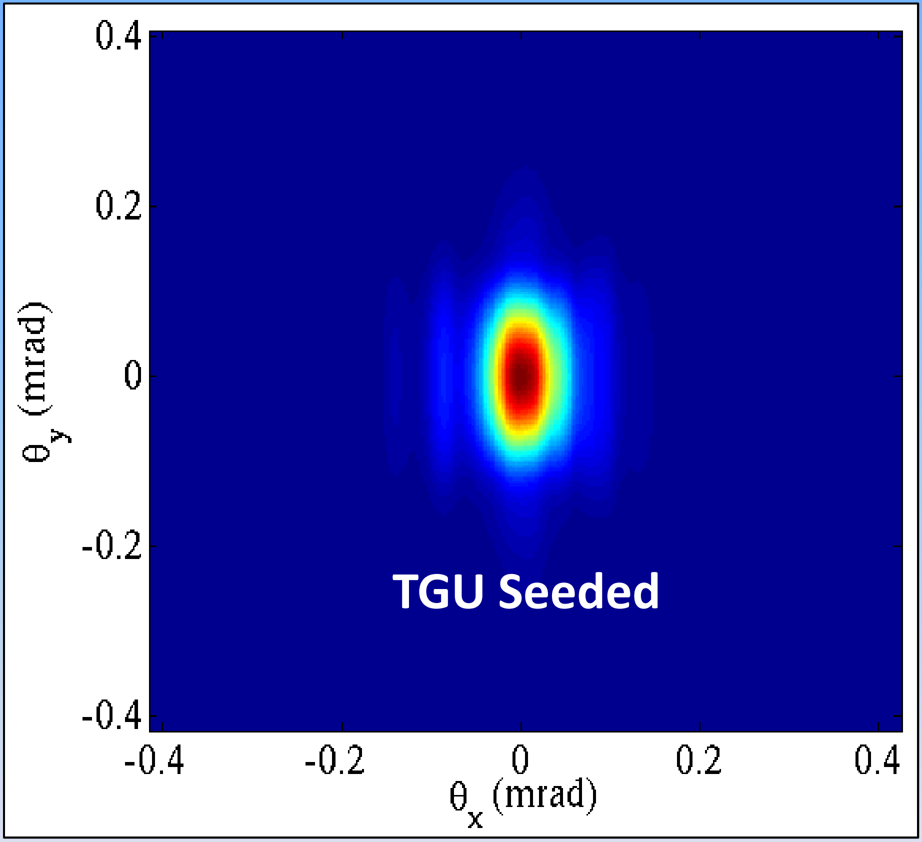


THUNDER TGU improves power by 1 to 2 orders, seeding with HHG reaches saturation in 5 m!

Transverse Mode Pattern

- Flat beam generates multiple horizontal modes
- Can be improved by seeding (HHG 500 kW, 50 um spot size)



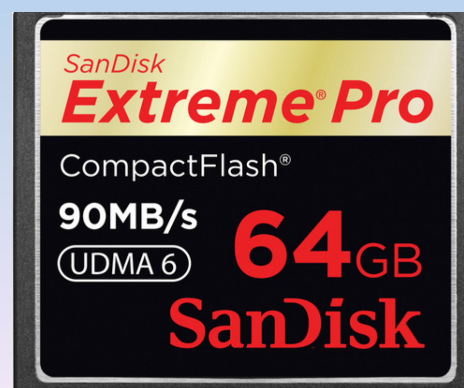


- SASE transverse modes be improved by stronger transverse gradient
  ➔ smaller transverse aspect ratio (see next SC example)

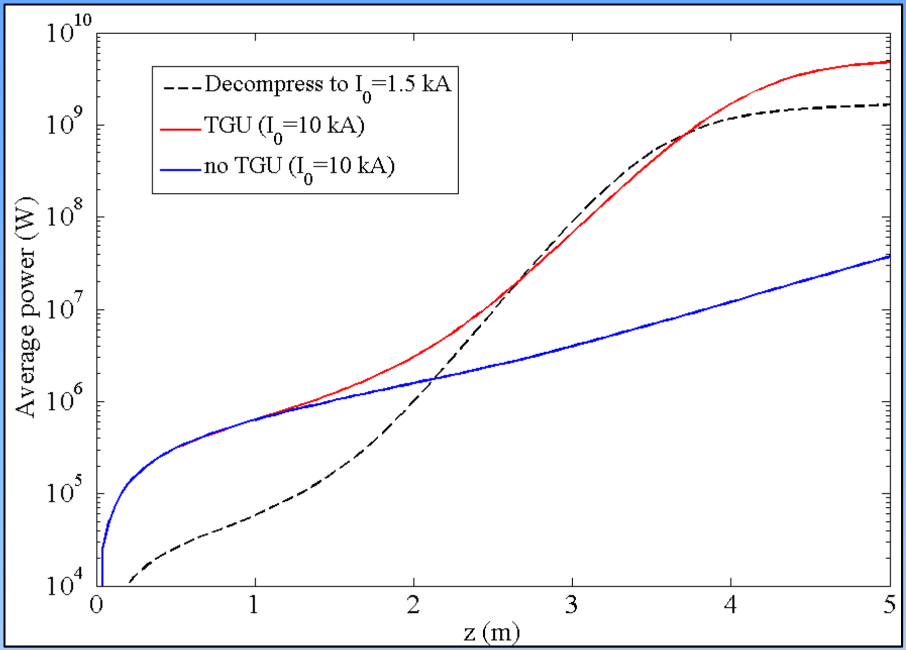
Compact soft x-ray FELs

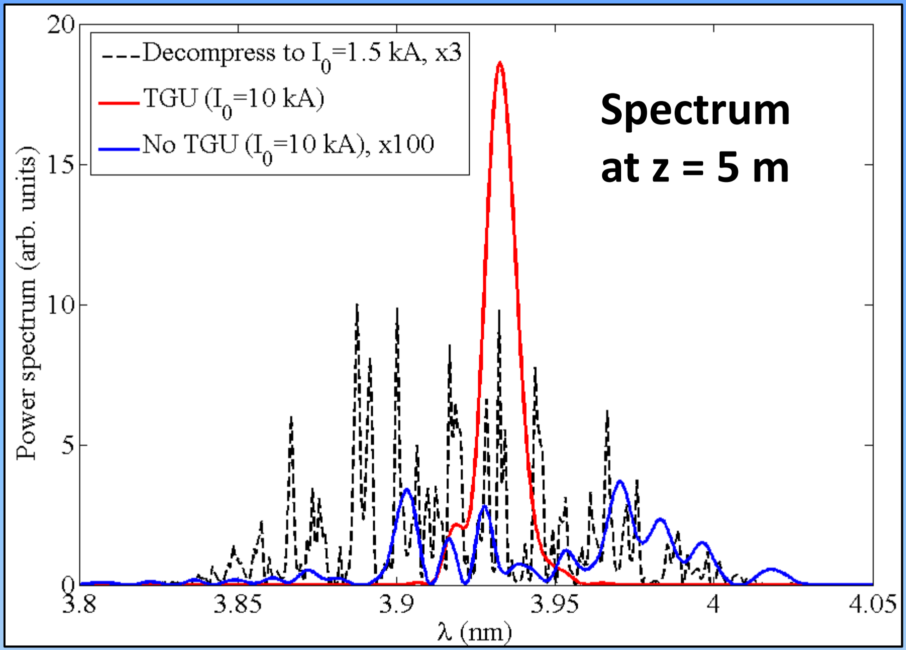
- 1GeV, 10kA, 10 MeV energy spread;
- 0.1um emittance; 5 fs (50 pC)
- **5-m SC undulator λ_u = 1 cm, K = 2;**
- Transverse gradient κ **= 150 m^{-1}**
- Radiation wavelength λ_1 = 3.9 nm
- For TGU, dispersion η = 0.01 m, trans. beam size 100um x 15um

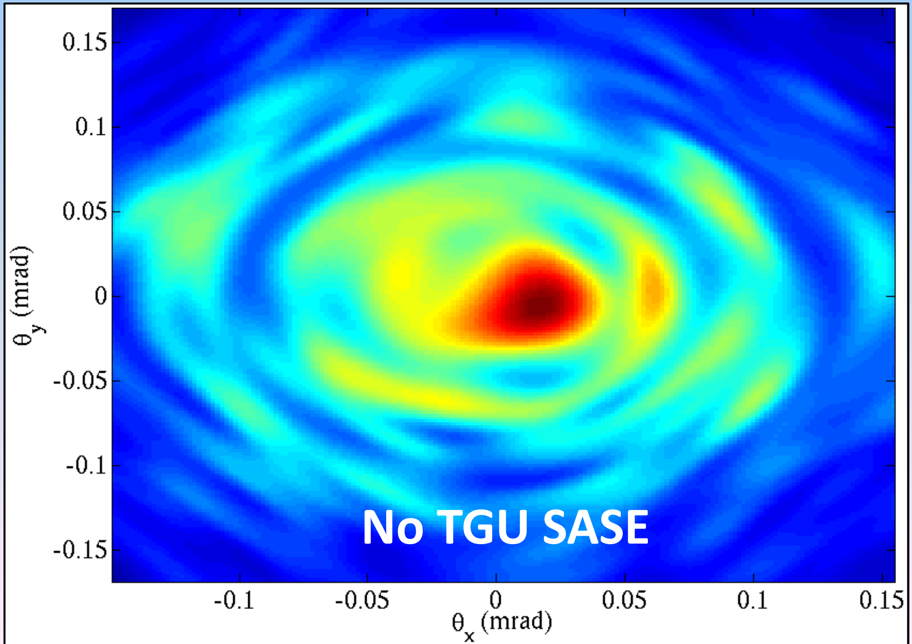
→ **CompactFLASH (cFLASH)?**

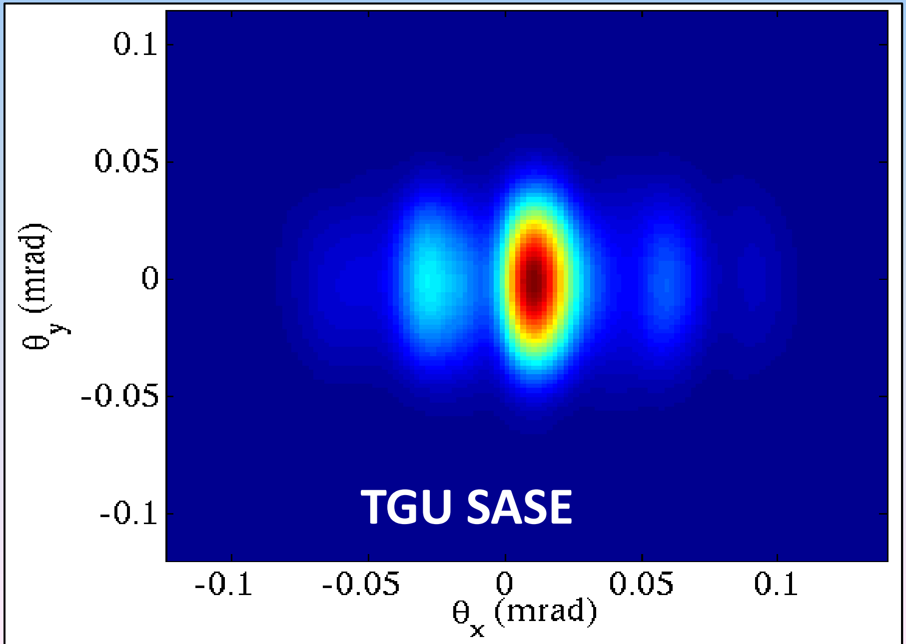


Simulations at 3.9 nm









Insensitive to Energy jitter

- TGU is insensitive to energy jitters (energy jitters → transverse position jitters), no change in FEL resonant wavelength

- Good for laser plasma accelerators (currently at a few % energy jitters)

- Good for a seeded FEL since wavelength is fixed

Summary

- Transverse Gradient Undulator appears to be a good fit to LPAs.
- Two orders of magnitude power gain has been obtained in EUV and soft x-ray examples.
- TGU wavelength is insensitive to energy jitters.
- LBL THUNDER undulator may provide proof of principle.
- TGU can be applied to other type of FELs/accelerators with further development.

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