Laser Wakefield Accelerated Electron Beam Monitoring and Control

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Norman Rostoker Memorial Symposium 8/24~8/25/2015

Relation to Norman

- Mail from Toshi, Subject Header: grand son
- …academic grandson of Norman…
- Numerical investigation of a plasma beam entering transverse magnetic fields,
  - J. Koga, J. L. Geary, T. Fujinami, B. S. Newberger, T. Tajima and N. Rostoker,
  - Journal of Plasma Physics 42, 91-110, (1989)
- Impact: confidence boost

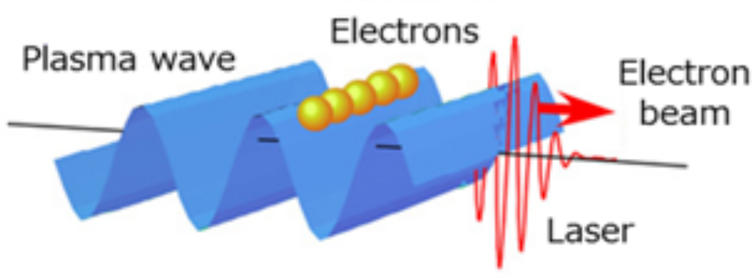
ImPACT: Ubiquitous Power Laser for Achieving a Safe, Secure and Longevity Society (PM: Y. Sano)

Acceleration by solid-state device (radio waves)

Acceleration gradient: 50 MV/m

Replaced by

Acceleration by plasma device (laser)

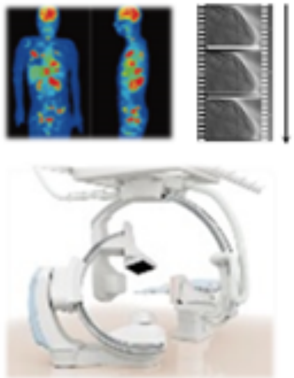


100 GV/m (Acceleration length: ~1/1000)

T. Tajima and J. M. Dawson, 1979, Phys. Rev. Lett. 43, 267

XFEL（SACLA） Conception of tabletop XFEL

Diagnosis and life-extension of structures



Advanced medical solutions

* XFEL: X-ray Free Electron Laser, a marvelous laser enabling atomic level analysis. Currently requires a kilometer-order accelerator facility.

Project 1: Laser Acceleration and XFEL demonstration

Beam Measurement and Control

- Measurement
  - Frequency Domain Interferometry and Holography
  - Betatron radiation
- Control
  - Laser Stability
  - Phase space rotation
  - Beam injection
  - Radiative Beam cooling

Desired electron beam parameters for standard undulator

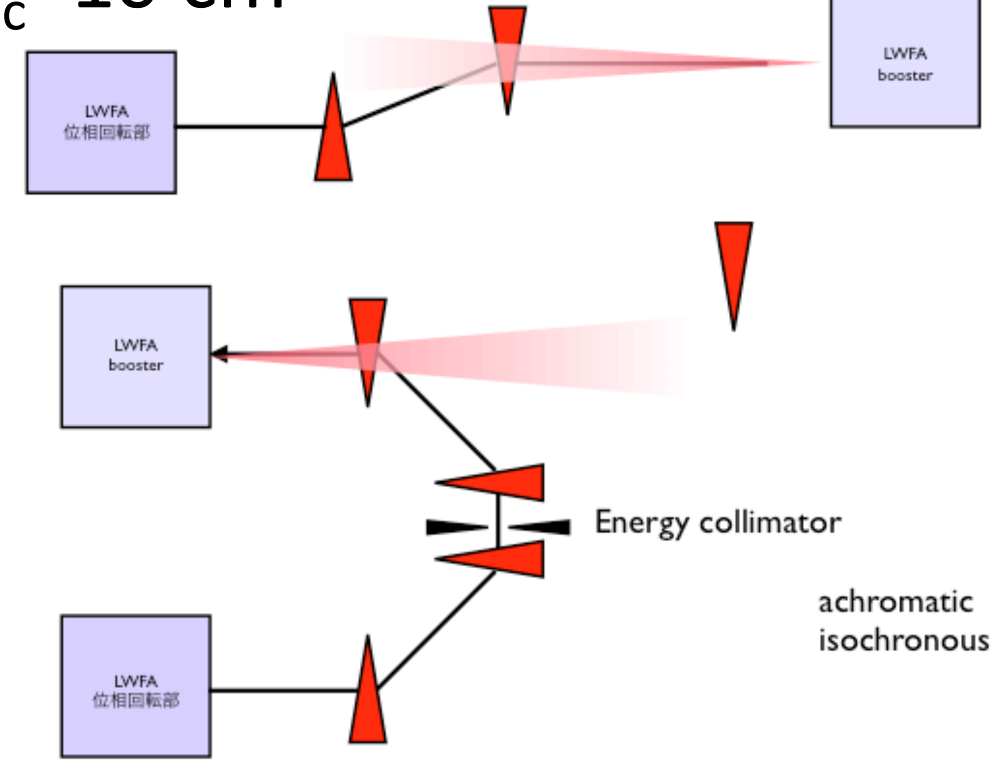
- Energy E> 1 GeV
- Charge Q~10 pC (10^7 electrons)
- Stability
- Emittance ε_n<0.1 mm mrad
- Energy Spread $\Delta E/E \sim 10^{-3} - 10^{-4}$

Laser Wakefield Accelerated Electrons

- Energy >1 GeV ☑
- Charge Q~10 pC (10^7 electrons) ☑
- Stability↗
- Emittance $\varepsilon_n \sim \pi$ mm mrad
- Energy Spread $\Delta E/E \sim 10^{-2}$

Considering Staged Acceleration

- Injector E~30 MeV L_{acc}~mm
- Phase Rotator LWFA
- Booster E~1 GeV L_{acc}~10 cm



Beam injection: Sharp Density Gradient

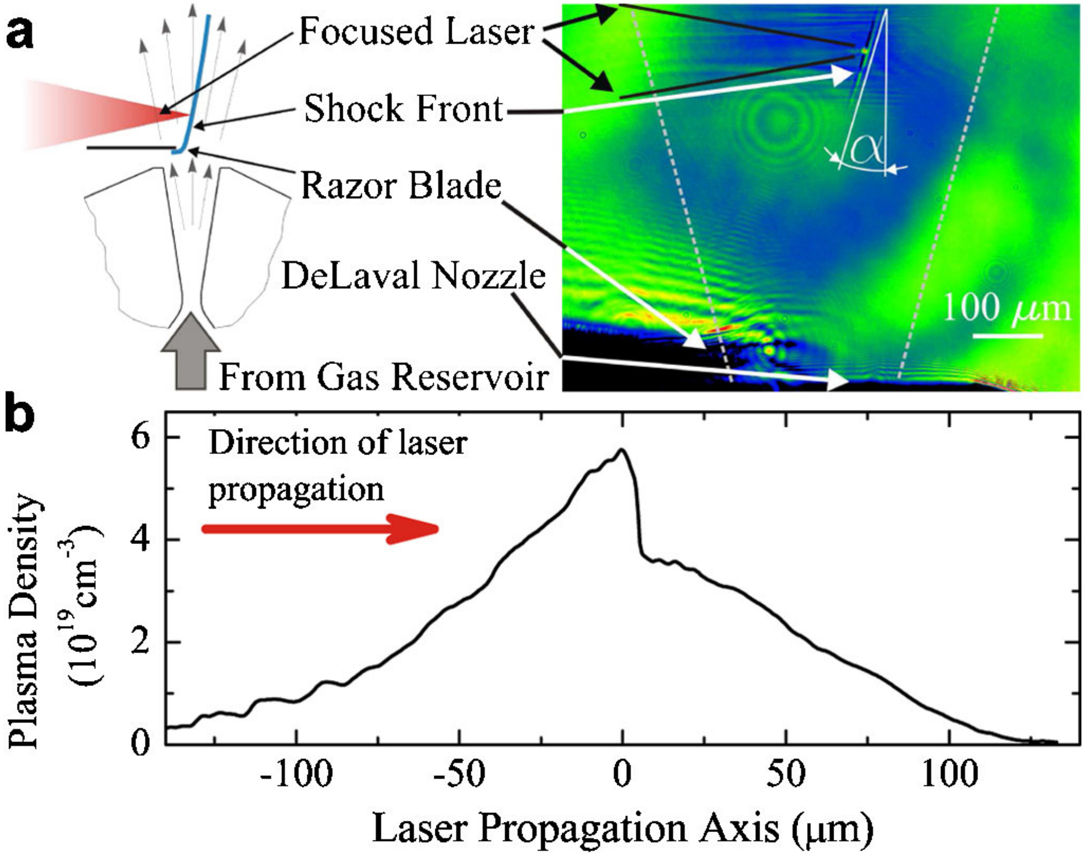
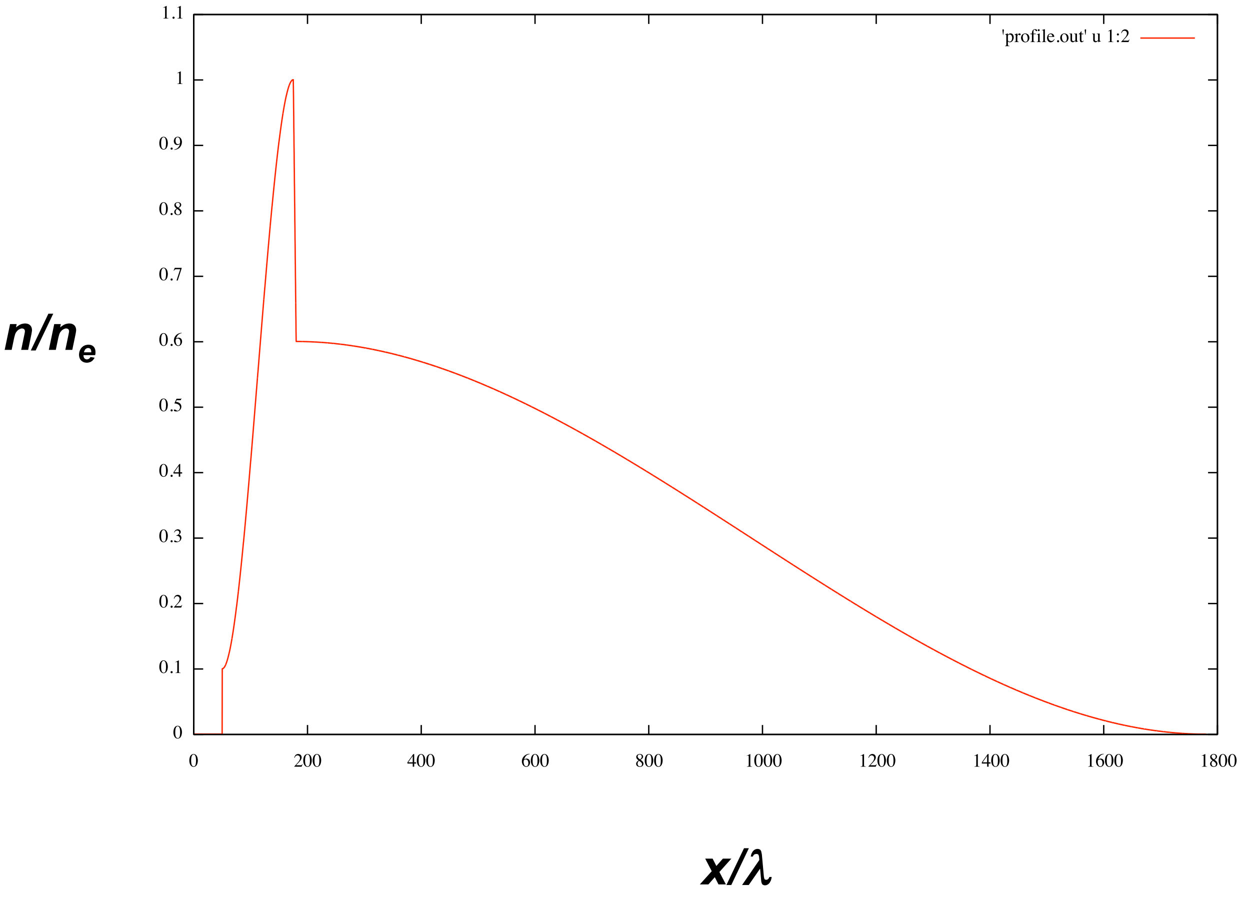


Figure 1 from Schmid et al., Phys. Rev. ST Accel. Beams 13, 091301 (2010)

Theory:
S. V. Bulanov, et al., Phys. Rev. E 58, R5257 (1998)
A. B. Brantov, et al., Phys. Plasmas 15, 073111 (2008)

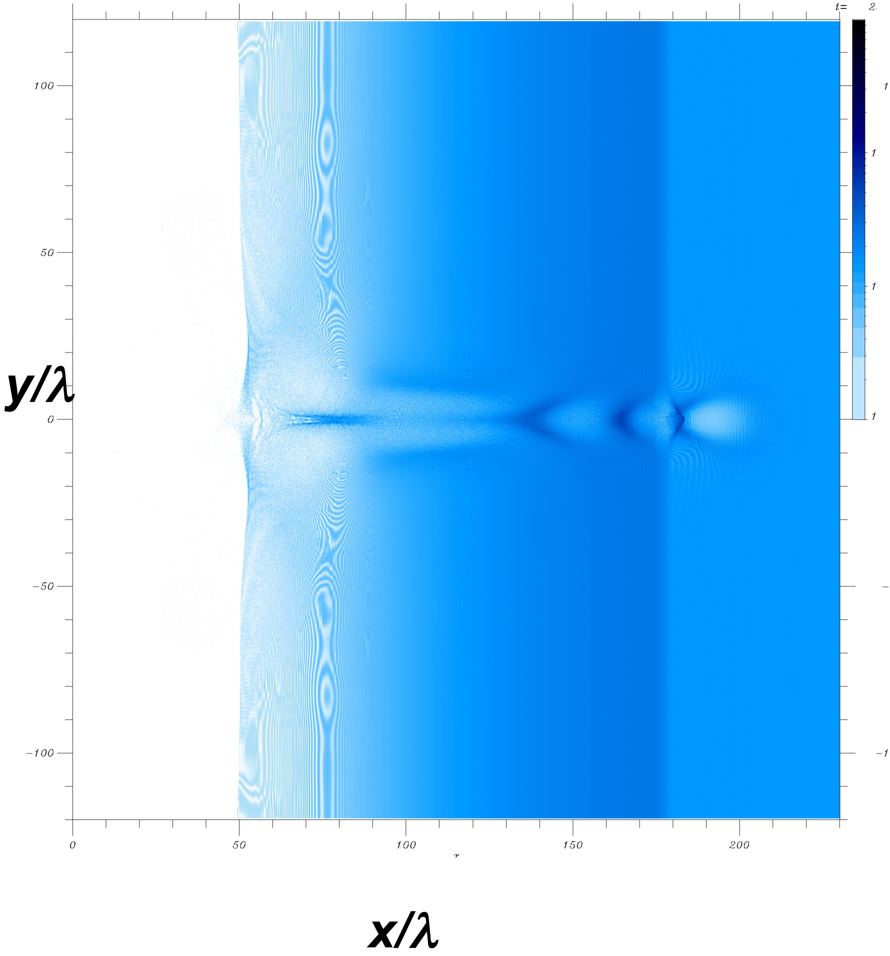
2D PIC Simulations

- Plasma
  - Peak density $\omega_{pe}/\omega_0=0.05$
  - gradient scale length $5\ \lambda_0$
- Laser
  - pulse length $12.5\ \lambda_0$
  - pulse focus $12.5\ \lambda_0$
  - focus point $175\ \lambda_0$
  - $a_0=1.5$
- Moving frame
  - $300\ \lambda_0$
  - $240\ \lambda_0$
  - $\Delta_x=\lambda_0/16$
  - $\Delta_y=\lambda_0/8$
  - 6 particles/cell max

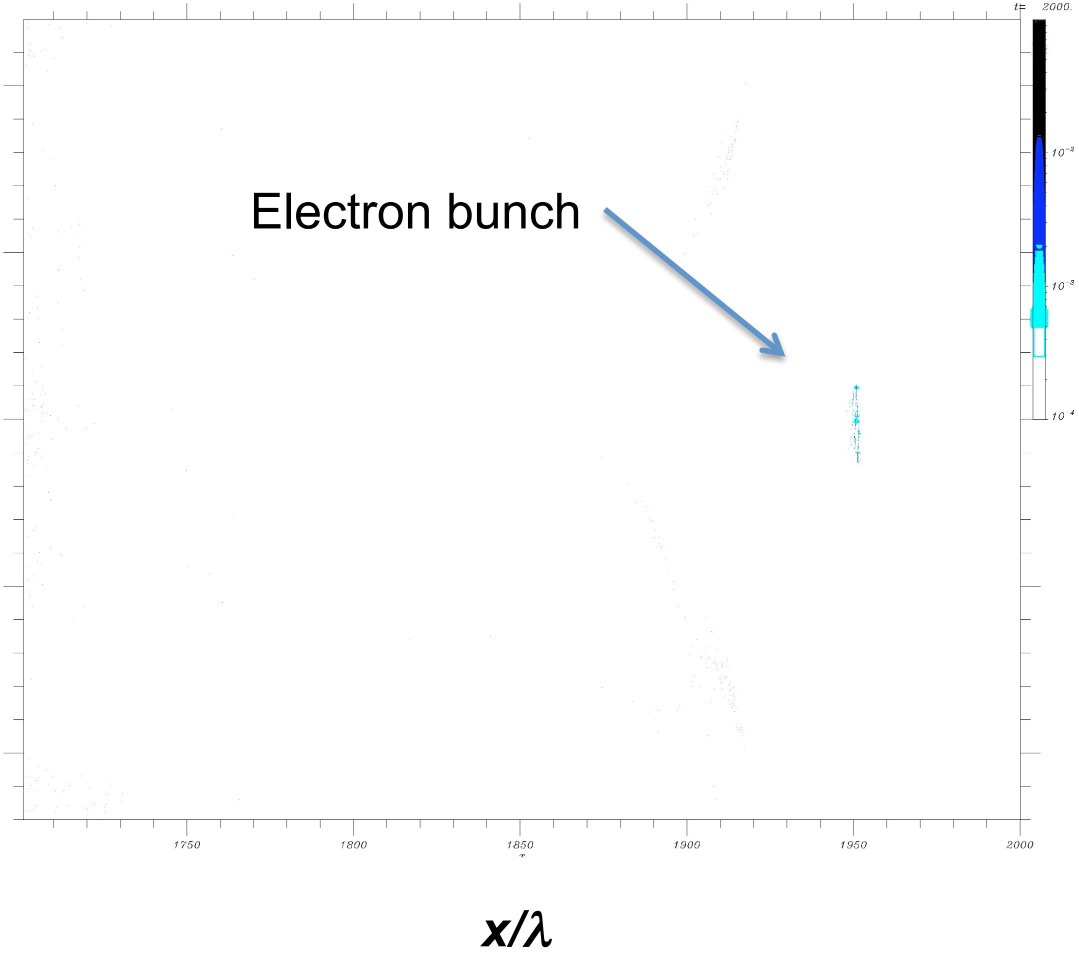


Electron density

Right after density gradient

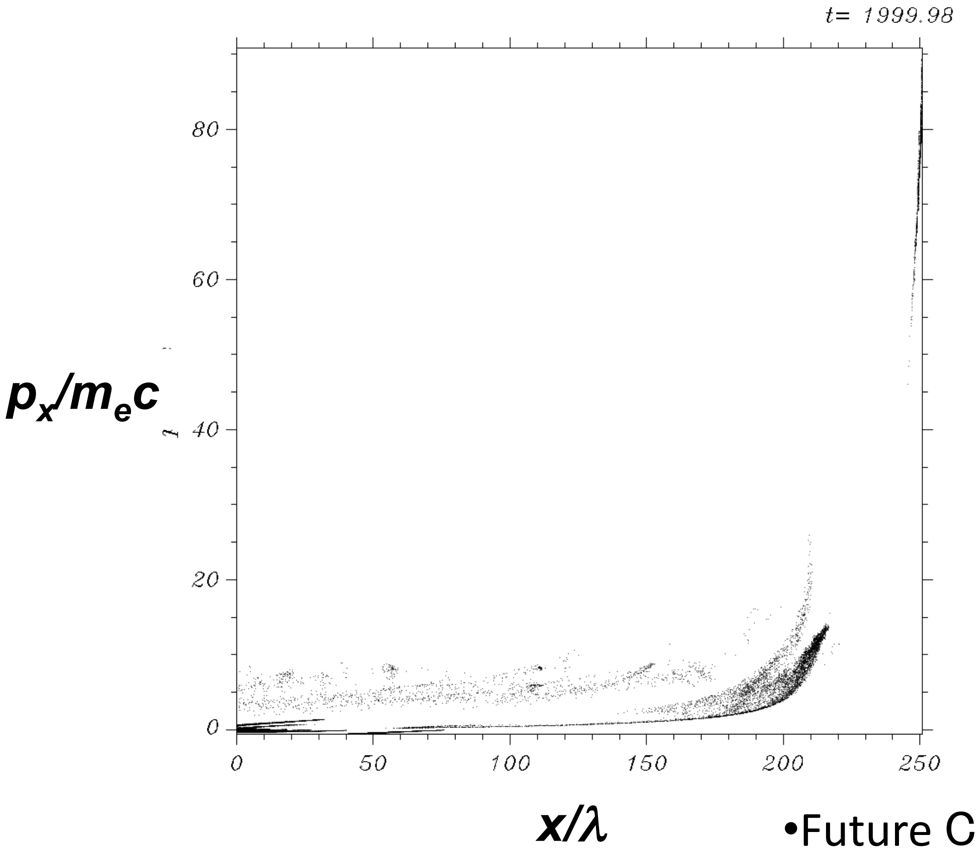


Exiting from plasma

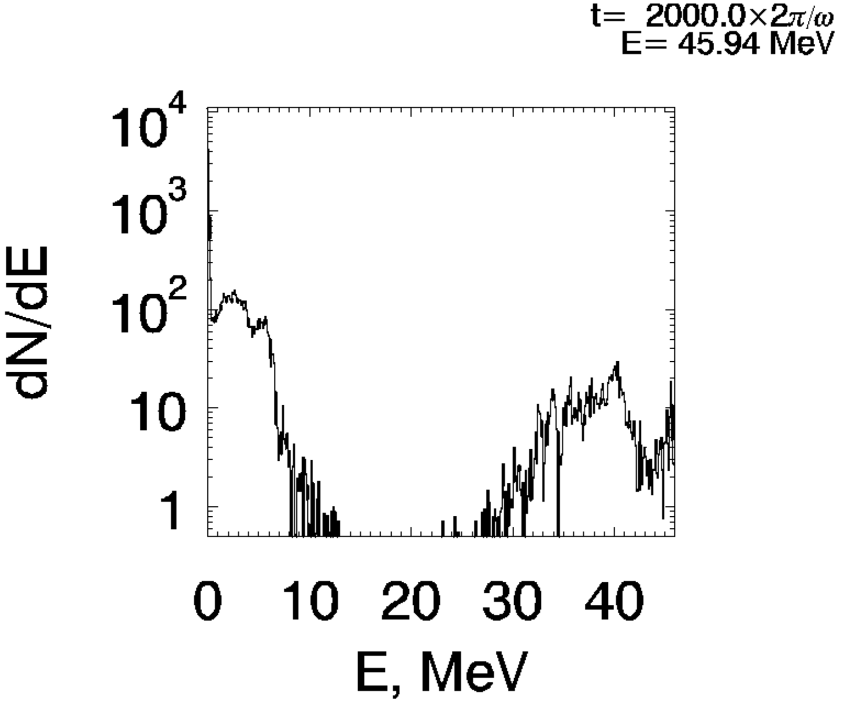

Electron bunch

Electron Beam

Phase space distribution



Energy Distribution



- Future Considerations
  - Fluid simulation
  - Optimization

Beam monitor, Betatron Radiation:

- Synchrotron spectrum, Jackson EM 3rd edition p. 682

$$\frac{1}{I}\frac{dI}{dy} = \frac{9\sqrt{3}}{8\pi} y \int_y^\infty K_{5/3}(x)dx$$

$$\omega_c = \frac{3}{2}\gamma^3\left(\frac{c}{\rho}\right)$$

$$y \equiv \frac{\omega}{\omega_c}$$

$$I = \frac{4\pi e^2\gamma^4}{3\rho}$$

- Integration using Quadpack routine, dqagi
- Modified Bessel functions $K_{5/3}(x)$ evaluated using Netlib routine, RKBESL

Betatron Radiation Parameters

- γ=2000 (1 GeV) $n_e = 10^{17}\,\mathrm{cm}^{-3}$ $r_\beta = 15\mu\mathrm{m}$
- Corde et al., Rev. Mod. Phys. **85**, 1 (2013) Eq (10)

$$\omega_c = \frac{3}{2} K\gamma^2 \frac{2\pi c}{\lambda_u}$$

$$\lambda_u = 4.72\times 10^{10}\sqrt{\gamma / n_e\left[\mathrm{cm}^{-3}\right]} = 6675\mu\mathrm{m} \sim 0.7mm$$

L

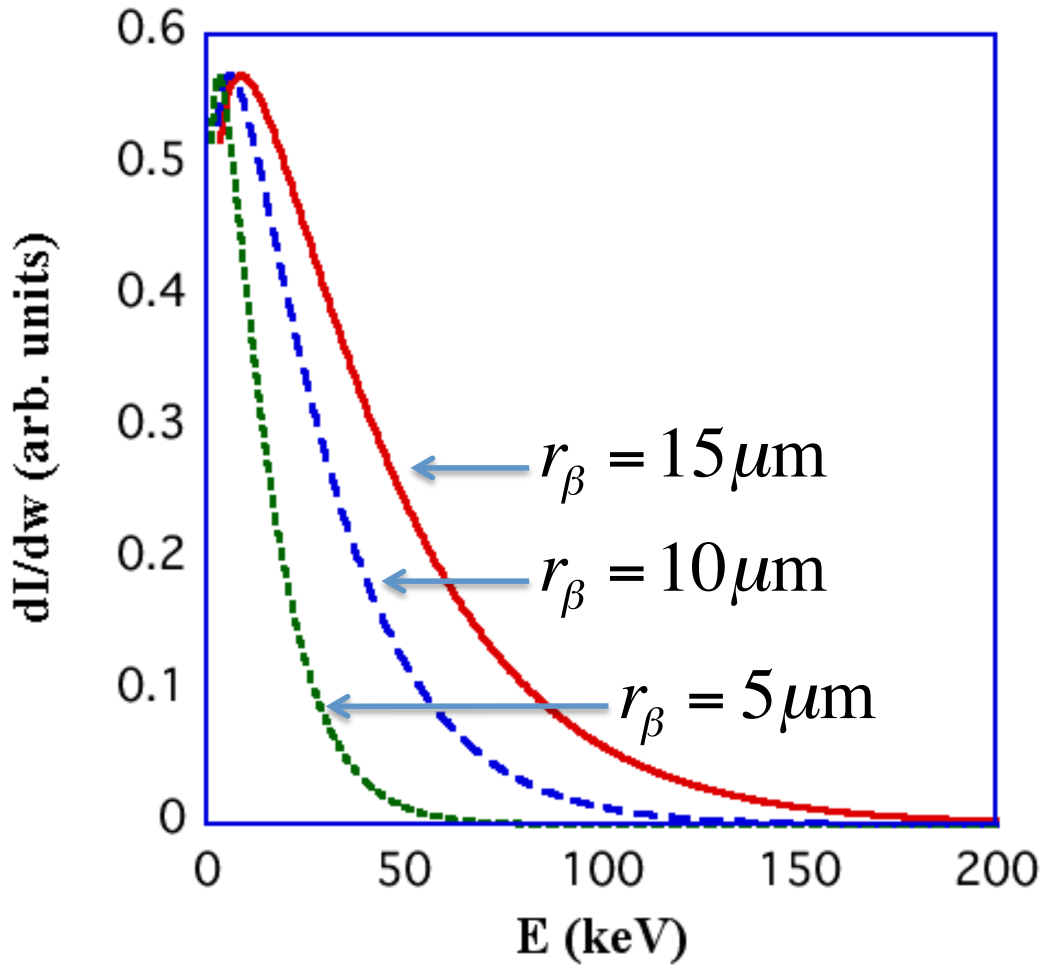
L_{acc}~10 cm

$$K = 1.33\times 10^{-10}\sqrt{\gamma n_e\left[\mathrm{cm}^{-3}\right]}\, r_\beta\left[\mu\mathrm{m}\right] = 28.2$$

$$\hbar\omega_c = 31.45\ \mathrm{keV}$$

Quantum correction small $\hbar\omega / E << 1$

Spectra



Need to compliment with FDI or FDH measurements

Kneip et al., PRST 15, 021302 (2012): Transverse electron beam emittance, “knife edge” x-rays source size, electron beam divergence, electron energy

Energy Spread: Transverse–Gradient Undulator (TGU)

- Large energy spread $\Delta E/E \sim 10^{-2}$
- Huang et al PRL 2012
- Zhang et al Opt Exp 2014
- Baxevanis et al PRSTAB 18, 010701 (2015)
  - Higher order modes in transverse space
  - transverse coherence loss

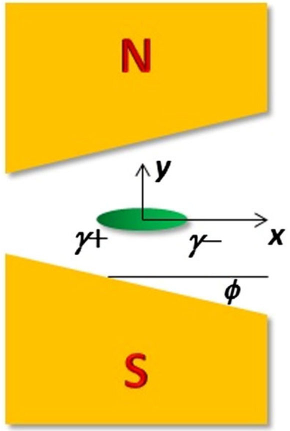


FIG. 1 (color online). Schematic of a transverse gradient undulator (TGU). The undulator poles are canted, which introduces a linear dependence of the vertical field with x. The constant field gradient depends on the cant angle ϕ.

Fig 1 from Baxevanis et al. PRSTAB 17, 020701 (2014)

PRL **111,** 084801 (2013) PHYSICAL REVIEW LETTERS week ending 23 AUGUST 2013

Using Off-Resonance Laser Modulation for Beam-Energy-Spread Cooling in Generation of Short-Wavelength Radiation

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To improve temporal coherence in electron beam based light sources, various techniques employ frequency up conversion of external seed sources via electron beam density modulation; however, the energy spread of the beam may hinder the harmonic generation efficiency. In this Letter, a method is described for cooling the electron beam energy spread by off-resonance seed laser modulation, through the use of a transversely dispersed electron beam and a modulator undulator with an appropriate transverse field gradient. With this novel mechanism, it is shown that the frequency up-conversion efficiency can be significantly enhanced. We present theoretical analysis and numerical simulations for seeded soft x-ray free-electron laser and storage ring based coherent harmonic generation in the extreme ultraviolet spectral region.

DOI: 10.1103/PhysRevLett.111.084801 PACS numbers: 41.60.Cr

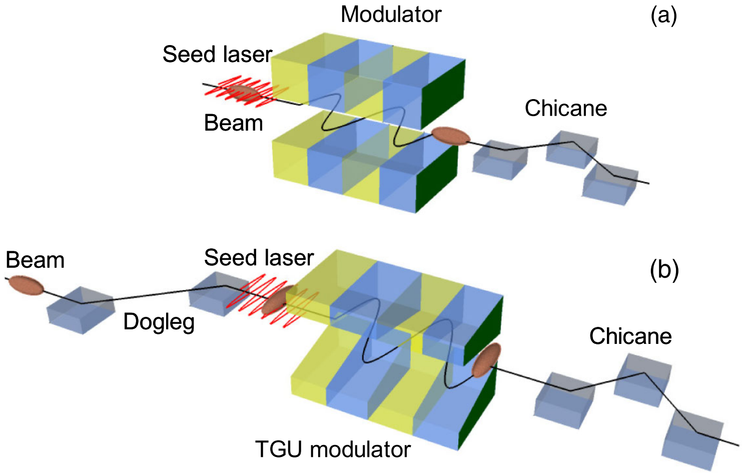

FIG. 1 (color online). A standard-HGHG system (a) consists of a modulator undulator and a dispersive section. The proposed cooled-HGHG scheme (b) includes a dogleg, a modulator undulator with transverse gradient, and a chicane.

Radiative Beam Cooling

- Telnov PRL 1997
- Yokoya NIMA 2000
- Esarey NIMA 2000
  - Cooling Equations (25) and (22)
  - Quantum fluctuations Eqs. (33) and (35)

$$E_{\text{rad}} \propto \left(\gamma m c^2\right)^2$$

$$\frac{\sigma_\gamma}{\langle\gamma\rangle} \approx \frac{\dfrac{\sigma_{\gamma_0}}{\langle\gamma_0\rangle}}{\left(1+\dfrac{z}{L_R}\right)}$$

$$L_R(\text{cm}) \approx \frac{337\lambda_0{}^2(\mu\text{m})}{\text{a}_0{}^2\gamma_0} \approx \frac{4.71\times10^{20}}{I\left(\text{W/cm}^2\right)E_{b0}(\text{MeV})}$$

$$\left(\frac{\sigma_\gamma}{\gamma}\right)_{\text{min}} \approx \left(\frac{\alpha_{\text{cr}}\lambda_{\text{C}}\gamma}{\lambda_0}\right)^{1/2}$$

$$\varepsilon_{\text{n,min}} \approx \frac{\alpha_{\text{cr}}\gamma_\perp{}^2\beta^*\lambda_{\text{C}}}{2\lambda_0}$$

$$\omega_{\text{cr}} = \alpha_{\text{cr}}4\gamma_0{}^2\omega_0$$

$$\lambda_{\text{C}} = \frac{h}{mc} = 2.426\text{x}10^{-10}\ \text{cm}$$

$$\gamma_\perp = \left(1+a_0{}^2\right)^{1/2}$$

$$\alpha_{\text{cr}} \approx 1 \qquad a_0{}^2 << 1$$

$$\alpha_{\text{cr}} \approx \frac{3a_0}{2} \qquad a_0{}^2 >> 1$$

β^* beta-function of the beam

Estimations

- Esarey NIMA 2000
  - γ_0=400 (200 MeV)
  - λ_0=1 μm
  - a_0=5.3 (7.7x10^{19} W/cm^2)
  - L_R~300 μm

$$\left(\frac{\sigma_\gamma}{\gamma}\right)_{\min} \approx 0.09$$

$$\varepsilon_{\mathrm{n,min}} \approx 3 \text{ mm-mrad}$$

$$\text{assuming } \beta^* = 1 \text{ cm}$$

- FEL
  - γ_0=2000 (1 GeV)
  - λ_0=1 μm
  - a_0=85 (1x10^{22} W/cm^2)
  - L_R~0.5 μm

$$\left(\frac{\sigma_\gamma}{\gamma}\right)_{\min} \approx 0.8!$$

$$\varepsilon_{\mathrm{n,min}} \approx 11000 \text{ mm-mrad!}$$

$$\text{assuming } \beta^* = 1 \text{ cm}$$

Suppression of Quantum fluctuations

- Huang et al PRL 1995
  - Continuous focusing channel
  - Recoil like Mössbauer effect

Undulator regime

$$\gamma\theta_p << 1$$

$$\theta_p = \frac{p_{\mathrm{x,max}}}{p_z}$$

- Huang et al PRL 1998

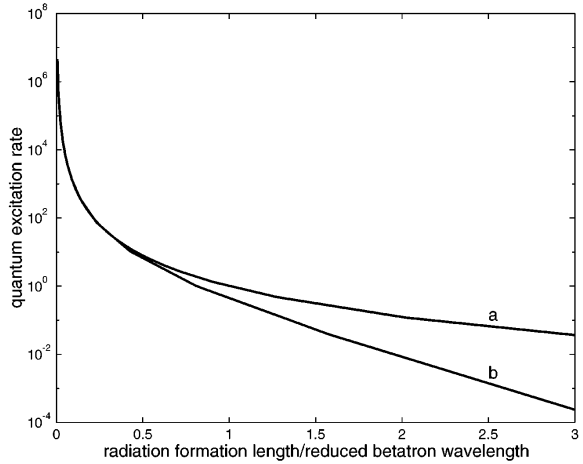

FIG. 1. Quantum excitation rate in units of $\Gamma_b \lambda\!\!\!^{-}_c$, predicted by (*a*) the quasiclassical model, i.e., the second term of Eq. (28), and (*b*) the quantum mechanical perturbation approach, i.e., the second term of Eq. (27).

Fig 1 from Huang et al PRL 80 (1998) 2318

ρ bending radius

$$\beta = \frac{c}{\omega_\beta}$$

$$\omega_\beta = \sqrt{\frac{K_e c^2}{E_s}}$$

$$\frac{\rho}{\gamma} \geq \beta$$

$$E_s = \sqrt{m^2c^4 + p_s{}^2c^4}$$

$$K_e = K + \frac{\left[p_0{}^2c^2 + 3\left(p_s - p_0\right)p_0c^2\right]}{E_s\rho^2}$$

- Sub-μm size channels→Carbon nanotubes
  - Y. M. Shin, et al., NIMB 355, 94 (2015)

Conclusions

- Stable injection beams possible
- Injection with larger energy spread
  - Staged acceleration
  - Or TGU
- Cooling possible
- Measurement possible with betatron radiation

Acknowledgements

J. K. Thanks T. Tajima, X. Zhang, C. Lau for fruitful discussions

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