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


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 $Q \sim 10$ pC ($10^7$ electrons)
- Stability
- Emittance $\varepsilon_n < 0.1$ mm mrad
- Energy Spread $\Delta E/E \sim 10^{-3} - 10^{-4}$
Laser Wakefield Accelerated Electrons

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

- Injector $E \sim 30$ MeV $L_{\text{acc}} \sim \text{mm}$
- Phase Rotator LWFA
- Booster $E \sim 1$ GeV $L_{\text{acc}} \sim 10$ cm
Beam injection: Sharp Density Gradient

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

Theory:
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

![Graph of $n/n_e$ vs $x/\lambda$]
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

• $\gamma = 2000 \text{ (1 GeV)}$ \quad $n_e = 10^{17} \text{ cm}^{-3} \quad r_\beta = 15 \mu\text{m}$

• Corde et al., Rev. Mod. Phys. 85, 1 (2013) Eq (10)

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

\[ \lambda_u = 4.72 \times 10^{10} \sqrt{\frac{\gamma}{n_e [\text{cm}^{-3}]}} = 6675 \mu\text{m} \sim 0.7 \text{mm} \quad L_{\text{acc}} \sim 10 \text{ cm} \]

\[ K = 1.33 \times 10^{-10} \sqrt{\gamma n_e [\text{cm}^{-3}] r_\beta [\mu\text{m}]} = 28.2 \]

\[ \hbar \omega_c = 31.45 \text{ keV} \]

Quantum correction small \quad $\hbar \omega / E \ll 1$
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 $\phi$. 

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

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

\[
L_R (\text{cm}) \approx \frac{337 \lambda_0^2 (\mu \text{m})}{a_0^2 \gamma_0} \approx \frac{4.71 \times 10^{20}}{I (\text{W/cm}^2) E_{b0} (\text{MeV})}
\]

- Quantum fluctuations Eqs. (33) and (35)

\[
\left( \frac{\sigma_{\gamma}}{\gamma} \right)_{\text{min}} \approx \left( \frac{\alpha_{\text{cr}} \lambda_C \gamma}{\lambda_0} \right)^{1/2}
\]

\[
\varepsilon_{n,\text{min}} \approx \frac{\alpha_{\text{cr}} \gamma \beta^* \lambda_C}{2 \lambda_0}
\]

\[
\lambda_C = \frac{h}{mc} = 2.426 \times 10^{-10} \text{ cm}
\]

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

\[
\alpha_{\text{cr}} \approx 1 \quad a_0^2 \ll 1
\]

\[
\alpha_{\text{cr}} \approx \frac{3a_0}{2} \quad a_0^2 >> 1
\]

\[
\beta^* \text{ beta - function of the beam}
\]

\[
E_{\text{rad}} \propto \left( \gamma mc^2 \right)^2
\]
Estimations

- **Esarey NIMA 2000**
  - $\gamma_0 = 400 \text{ (200 MeV)}
  - $\lambda_0 = 1 \text{ } \mu\text{m}$
  - $a_0 = 5.3 \text{ (7.7x10}^{19} \text{ W/cm}^2)$
  - $L_R = 300 \text{ } \mu\text{m}$

- **FEL**
  - $\gamma_0 = 2000 \text{ (1 GeV)}$
  - $\lambda_0 = 1 \text{ } \mu\text{m}$
  - $a_0 = 85 \text{ (1x10}^{22} \text{ W/cm}^2)$
  - $L_R = 0.5 \text{ } \mu\text{m}$

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

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

$\varepsilon_{n, min} \approx 3 \text{ mm-mrad}$ assuming $\beta^* = 1 \text{ cm}$

$\varepsilon_{n, min} \approx 11000 \text{ mm-mrad!}$ assuming $\beta^* = 1 \text{ cm}$
Suppression of Quantum fluctuations

• **Huang et al PRL 1995**
  – Continuous focusing channel
  – Recoil like Mössbauer effect

\[ \gamma \theta_p \ll 1 \]

Undulator regime

\[ \theta_p = \frac{p_{x,\text{max}}}{p_z} \]

• **Huang et al PRL 1998**

ρ bending radius

\[ \rho \geq \frac{\beta}{\gamma} \]

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

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

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

• Sub-μm size channels \( \rightarrow \) Carbon nanotubes
Conclusions

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

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