17TH ADVANCED BEAM DYNAMICS WORKSHOP ON
FUTURE LIGHT SOURCES

Free-Electron Radiation Sources Based on High-Contrast Energy Modulation of Electron Beams

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FREE-ELECTRON RADIATION SOURCES BASED ON HIGH-CONTRAST ENERGY MODULATION OF ELECTRON BEAMS*

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TALK OVERVIEW:

- **high contrast electron beam modulation ("relativistic interferometry")**
  - lab frame vs. bunch rest frame perspective
  - spontaneous radiation characteristics
- **modulation physics**
  - single-electron modulation
  - collective effects
  - 1-D approximation
- **bunching physics**
  - ballistic vs. dispersion-assisted bunching
  - compared to "high harmonic" FEL/OK
- **coherent source properties**
  - coherent vs. spontaneous power
  - contrasted with "high harmonic" FEL/OK
- **R&D**
  - electron beam modulation applications
  - radiation source development
- **summary**

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FEL parameter scaling in lab vs. electron bunch frame*:

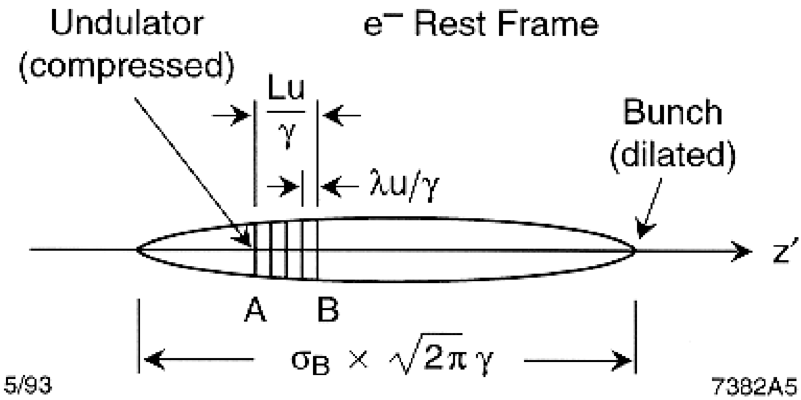


Table. Typical SASE FEL cases for a fixed undulator with K=3.67.

beam energy		0.3 GeV	1 GeV	5 GeV	15 GeV
FEL output		50 MW	1 GW	15 GW	50 GW
beam area		.0225 cm^2	0.0075 cm^2	7400 μ^2	2500 μ^2
γ^*		210	360	3600	10000
B_r	lab	0.436T	3.4T	130T	413T
B_r	beam	21g	94g	361g	413g
B_u	lab	1.3T	1.3T	1.3T	1.3T
B_u	beam	273T	468T	4680T	13000T
λ_u	lab	3cm	3cm	3cm	3cm
λ_u	beam	143μ	83μ	8.3μ	3μ
σ_B	lab	1000μ	300μ	40μ	30μ
σ_B	beam	21cm	10.8cm	14.4cm	30cm
L_{sat}	lab	10m	20m	50m	100m
L_{sat}	beam	4.5cm	5.34cm	1.4cm	1cm

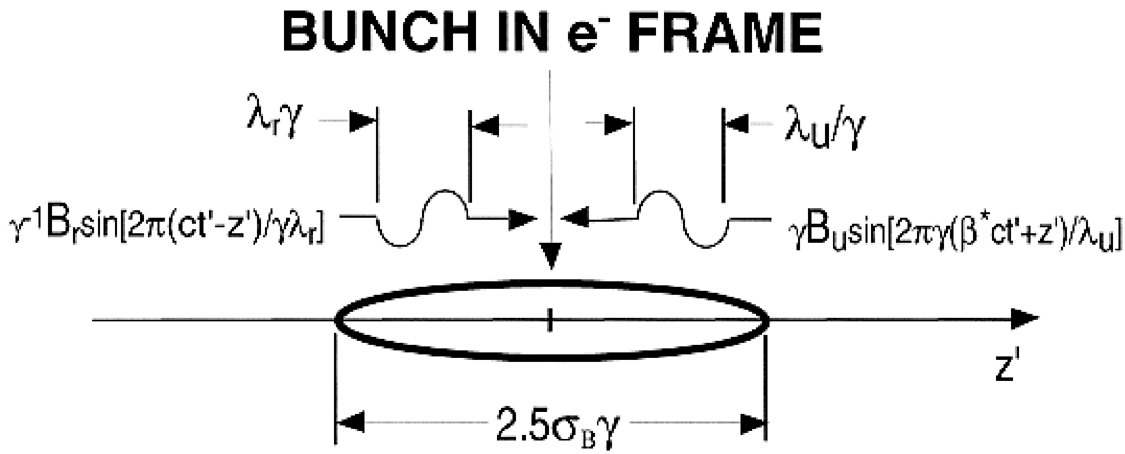
*Weizsacker-Williams approximation (Madey[a], Colson, et al)

[a] J. M. J. Madey, "Stimulated Emission of Bremsstrahlung in a Periodic Magnetic Field," Jour. Appl. Phys. 42(3), 1906(1971).

Impact of short-pulse IR/Visible/UV terawatt lasers:

- advent of terawatt lasers (e.g., C. P. J. Barty, C. L. Gordon III, and B. E. Lemoff, "Multiterawatt 30-fs Ti:sapphire Laser system," Optics Letters, 1994.) allows driving fields into the electron bunch rest frame that are comparable to or larger than the undulator field. This regime is 1-2+ orders beyond typical FEL radiation field levels in undulators.

- "Relativistic interferometry" becomes possible*.



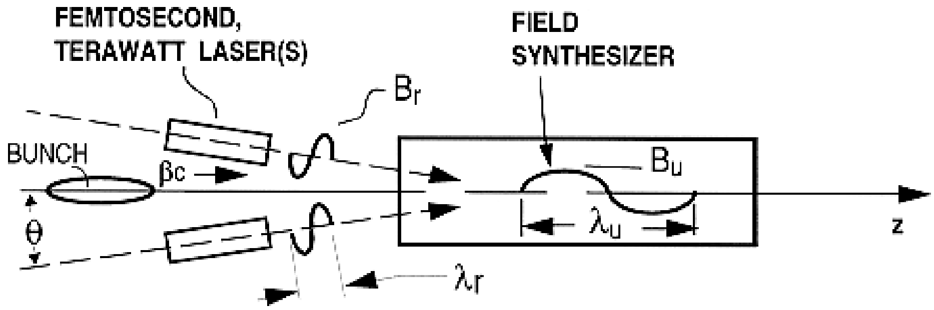
- criterion for "High Contrast" interference:

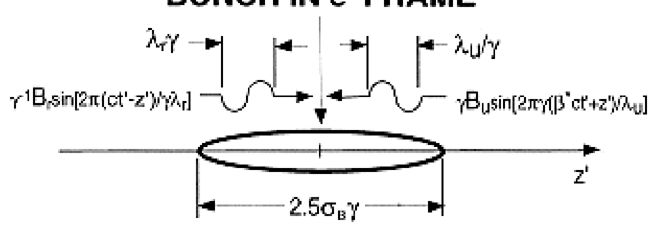
$$O(K_r) \cong O(K_u)$$

*R. Tatchyn, in Proc. Workshop on 4th Generation Light Sources, M.Cornacchia and H. Winick, eds., SSRL, Feb. 1992.

radiation source development:

- **short pulser/buncher***





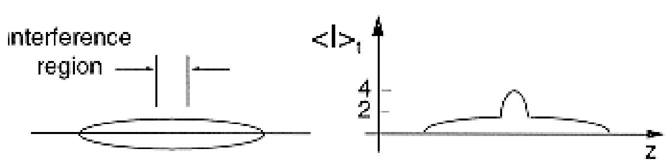
Conditions for maximum interference (θ small):

$$\lambda_r \cong (\lambda_u/2)\left((\gamma^*)^{-2}+\theta^2\right),$$

and

$$\lambda_r \cong 2B_u\left((\gamma^*)^{-2}+\theta^2\right).$$

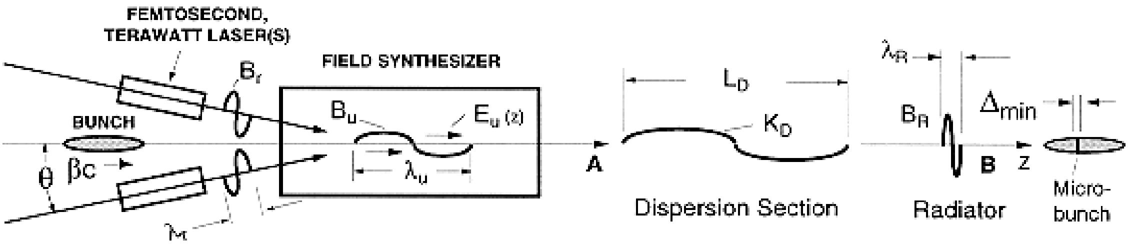
- **spontaneous radiation characteristics****



- only factor of 2 average intensity gain
- small photon number/pulse (10^1-10^3)
- evidently of limited interest for θ=0 r

*R. Tatchyn, NIM A358, 56(1995)
**R. Tatchyn, "Quantum-limited Temporal Pulse Generation," in *Proc. Workshop on 4th Generation Light Sources*, M.Cornacchia and H. Winick, eds., SSRL, Feb. 1992. p. 482 ff.

- **utilize energy modulation to compress region (coherent emission gain + wavelength reduction)**



Then

$$\ddot{x}' = -\left(\frac{qc}{m}\right)\{\gamma B_u \sin(\omega_u t' + k_u z' + \phi_u) + B_r \gamma^{-1} \sin(\omega_r t' - k_r z' + \phi_r)\} \ ,$$

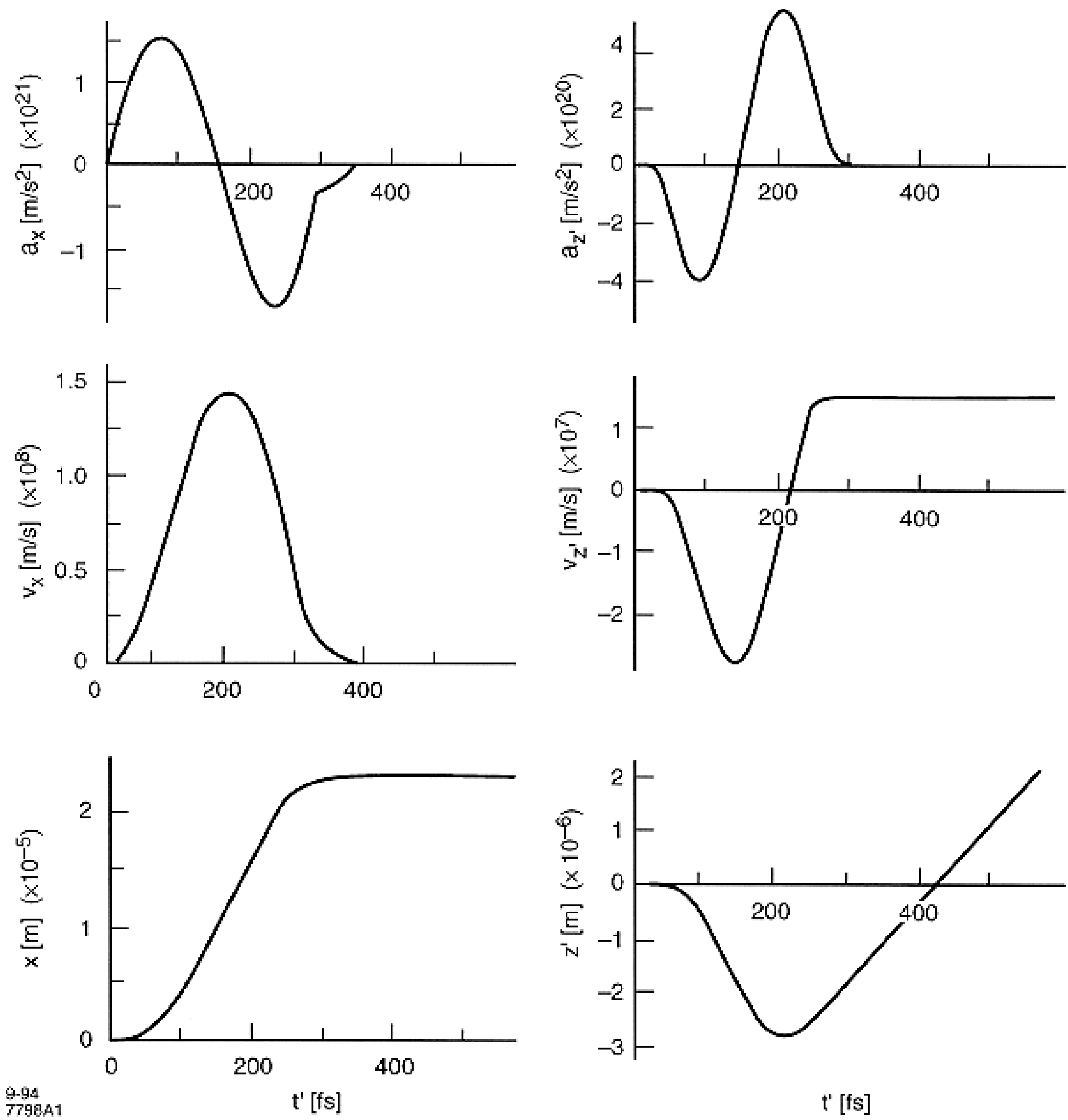
$$\ddot{z}' = \left(\frac{q}{m}\right)^2 \left(\frac{1}{2k_u}\right)\{\gamma^2 B_u^2 \sin 2(\omega_u t' + k_u z' + \phi_u) - B_r^2 \gamma^{-2} \sin 2(\omega_r t' - k_r z' + \phi_r) + 2 B_r B_u \sin((k_u + k_r) z' + (\phi_u - \phi_r))\} .$$

physics:

- for 1st field integrals=0, net v_X modulation=0
- 2nd field integrals need not =0
- modulation drives electrons toward energy minimum(a)
- net v_Z modulation=0 (averaged over z)

Example:

x (left) and z' (right) components of electron motion in the lab frame. Assumed parameters: $\gamma = 300$; $\lambda_r = 4800$Å; laser waist 0.1mm; laser power 4.3 TW; $\lambda_u = 8$cm; $B_u = 0.032$T. $v_x(0) = v_{z'}(0) = 0$.



practical performance parameters:

- **maximum normalized energy and velocity kicks (i.e., for $|\phi_r - \phi_u| = \pi/2$):**

$$\Delta\gamma \cong 2\pi\gamma K_r K_u,$$

and

$$\Delta\beta_Z \cong 2\pi K_r K_u / \gamma^2$$

- **corresponding energy and velocity kicks in the bunch frame:**

$$\Delta E' \cong 2\pi^2 m_e c^2 (K_r K_u)^2 \text{ [J]},$$

and

$$\Delta v_Z' \cong 2\pi c K_r K_u \text{ [m/s]}.$$

- **XRFEL:** $O(10^{-9}\text{-}10^{-12})$ **[entrance]** $< K_r <$ $O(10^{-5}\text{-}10^{-7})$ **[saturation]**
- **but also down to IR wavelengths,** $K_{r(FEL,OK)} << K_{r(HCM)}$

- **FEL $\Delta\gamma/\gamma$ per period** $\sim(1/N_u^2) \sim O(10^{-6})$ => **"adiabatic"**
- **HCM $\Delta\gamma/\gamma$ per period** $\sim O(10^{-1}\text{-}10^{-2})$ => **"high action" or "rapid"**

- **criterion for distinguishing a HCM system vs. a FEL or OK:**

$$(K_r K_u)_{HCM} >> (K_r K_u)_{FEL,OK}$$

collective dynamics:

- **Vlasov's equation:**

$$\frac{\partial f}{\partial t} + \vec{v} \cdot \frac{\partial f}{\partial \vec{r}} = \frac{e^2}{4\pi\varepsilon_0} \frac{\partial f}{\partial \vec{v}} \cdot \int \frac{\partial}{\partial \vec{r}} \frac{1}{\left|\vec{r} - \vec{r}'\right|} f(\vec{r}', \vec{v}', t) d\vec{r}' d\vec{v}'$$

- **assumptions in present work:**

  - dynamics non-linear

  - average velocities in bunch frame non-relativistic

- **simulation:**

  - 1-D approximation (good for assumed bunch parameters, with exception of "edge" effects)

  - particle interactions dominated by electrostatic field

  - radiative interactions ignored

  - modulation/bunching processes assumed sequential and independent (i.e., modulation "imprint" sets initial conditions; bunching follows)

- **bunching:**

  - ballistic

  - dispersion-assisted

- **1-D, non-relativistic approximation (In bunch frame):**

$$\frac{\partial f'}{\partial t'} + v'_{z'} \cdot \frac{\partial f'}{\partial z'} = -\frac{e}{4\pi\varepsilon_0 m\gamma}\left(\frac{E_{z'}}{\gamma_B^2}\right) \cdot \frac{\partial f'}{\partial v'_{z'}}$$

$$\rho' = e\int dv'_{z'} f' ; \quad E_{z'} = -\frac{1}{\varepsilon_0}\int \rho' \, dz'$$

- **for linear velocity modulation and uniform initial density, energy balance analysis yields:**

$$\Delta v'_{z(CR)} \cong \sqrt{\frac{q r_b \rho_B \lambda_u}{m_e \gamma^2 \varepsilon_0} \tan^{-1}\left(\frac{\lambda_u}{2\gamma r_b}\right)} \ [\mathrm{m/s}]$$

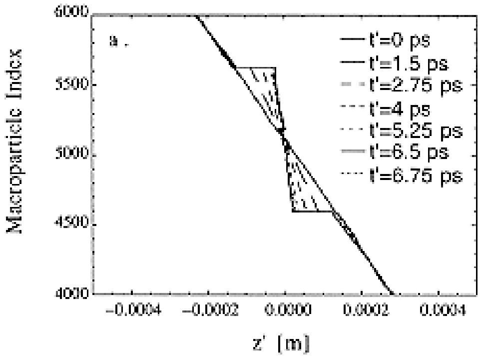
- **three regimes are predicted:**

I.	$\Delta v'_z < \Delta v'_{z(CR)}$	**(undermodulation)**
II.	$\Delta v'_z > \Delta v'_{z(CR)}$	**(overmodulation)**
III.	$\Delta v'_z \cong \Delta v'_{z(CR)}$	**(critical modulation)**

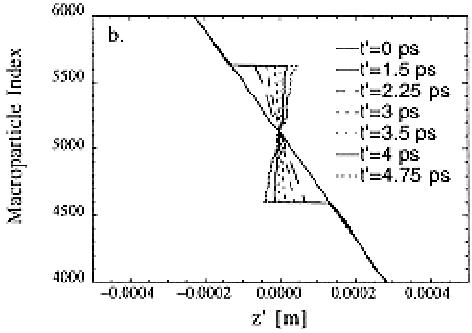
Simulation (ballistic bunching):

Beam parameters: γ=300; $\sqrt{2\pi}\sigma_B$=0.5 mm; r_b=100 μm; $N_e=10^{11}$; number of macroparticles$\cong 10^4$ (contained in a region of length $10\lambda_u/\gamma^*$ at the center of the bunch); electrons/macroparticle$\cong 8.9 \times 10^4$. Cylindrical electron beam with longitudinally Gaussian and transversely uniform density profiles. In (a.-c.) only the central 2000 macroparticles are shown.

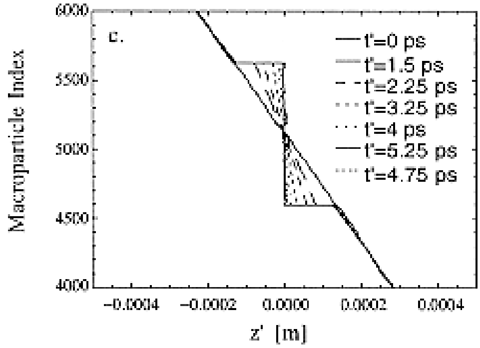
I. undermodulation



II. overmodulation

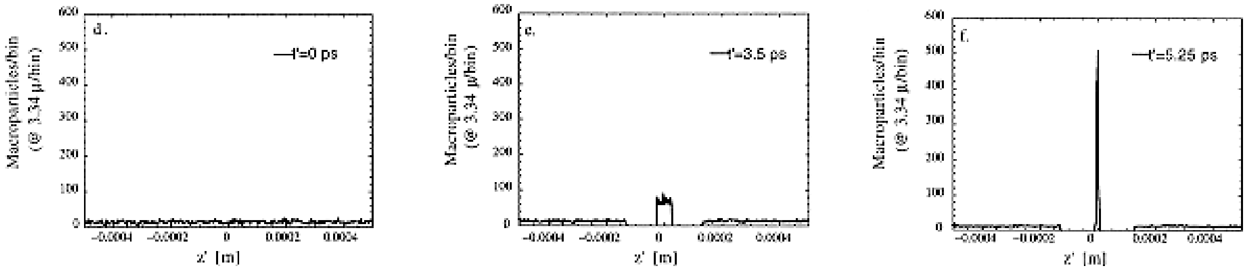


III. critical modulation

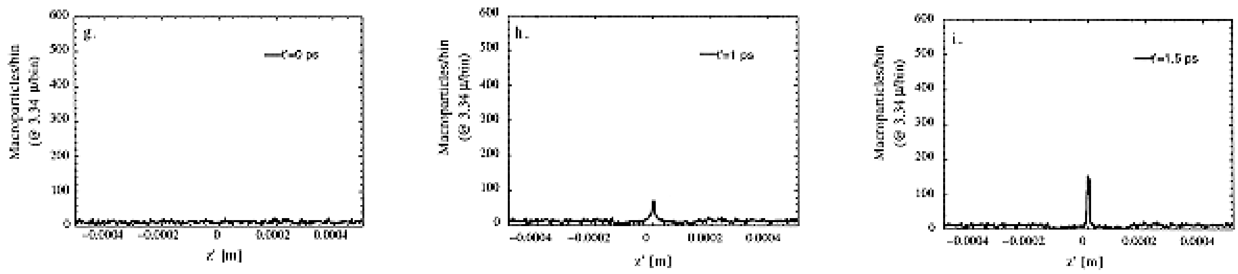


bunching and field distributions:

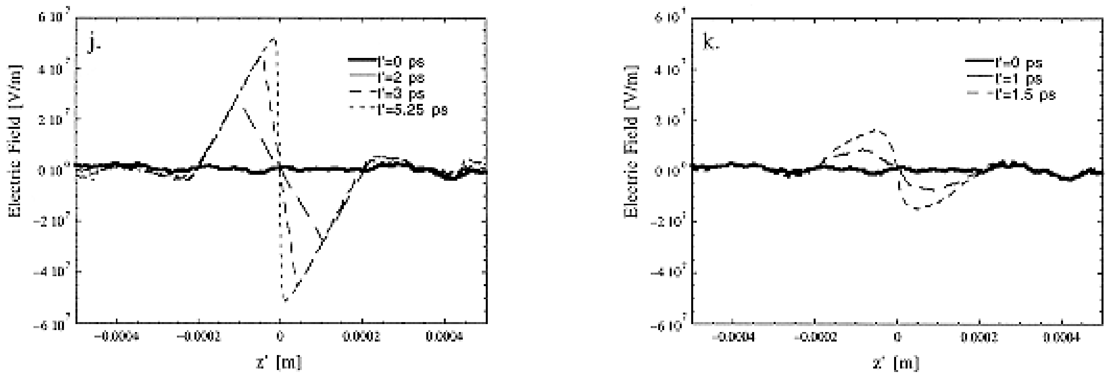
- bunching with linear velocity modulation (central 3700 macroparticles shown):



- bunching with sinusoidal modulation (central 3700 macroparticles shown):



- evolving field distributions in bunch frame: (j.) linear modulation. (k.) sinusoidal.

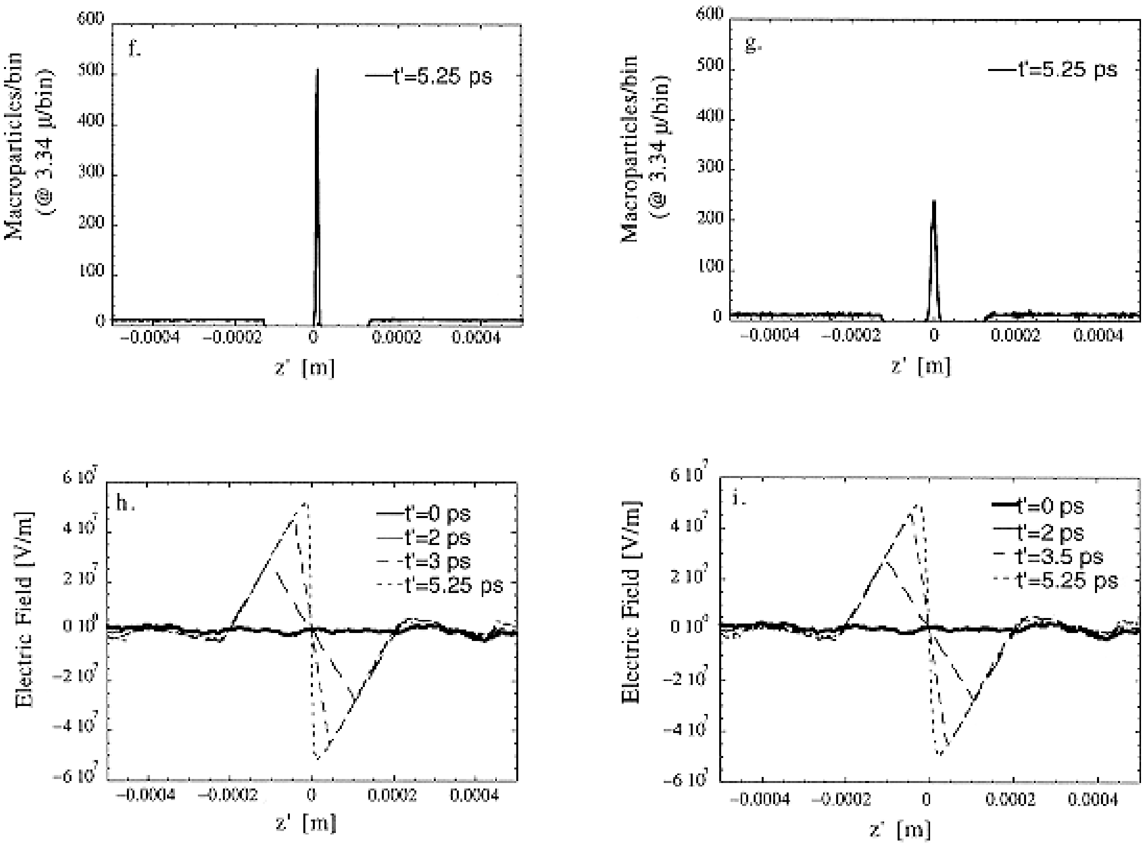


warm beam effects:

- **analytic approximation** for a circular Gaussian beam with horizontal and vertical angular spread sigmas σ_H', σ_V', and a relative energy spread sigma σ_ε.

$$\frac{\Delta_{min}}{\lambda_r} \approx \frac{2\gamma}{\Delta\gamma_{1N}}\sqrt{2\pi\sigma_\varepsilon^{\,2} + \left(\pi\left(\sigma_V'^{\,2} + \sigma_H'^{\,2}\right)\right)^2 \gamma_D^{*4}}$$

- **warm-beam simulations:** (g.) the effect of an 0.1% 1-σ energy spread is displayed vs. the cold beam profile in (f.). In (h.) and (i.) the growth of critically modulated (bunch frame) field distributions for σ_εs of 0.0% vs. 0.1% are shown.



- **fundamental distinctions between HCM and FEL/OK systems (review)**

FEL/OK	HCM
Modulation and bunching adiabatic. Relative energy change/period ~$O(10^{-6})$.	Modulation and bunching rapid. Relative energy change/period ~$O(10^{-2})$.
Electrons interact over "co-operation length" ~$N_u\lambda_r/10$.	Electrons interact over $O(1)$ period.
Self-consistent interactions through radiation+Coulomb fields essential to modulation/bunching.	Electron-scattered radiation plays an initially minor role. Self-consistent interactions through Coulomb fields dominate.
Dynamics can be linearized	Dynamics strongly non-linear
Modulation/bunching process periodic (quasi-periodic (chirped) in a tapered FEL).	Phase-space structure of the modulation/bunching process less restricted.
Modulated bunch typically $>>N_u\lambda_r/10$.	Modulated bunch region typically ~$O(\lambda_r)$

Selected radiative properties:

assume

$$\lambda_R \geq 4\gamma^{*2}\Delta_{min}$$

then for N_e electrons,

$$P_{SP} \cong N_e\left[\gamma^4 q^2 < \dot{v}_y^2 > /(6\pi\varepsilon_0 c^3)\right] \quad [MKS]$$

the maximum coherent power, P_{COH}, is given by

$$P_{COH} \cong N_e^2 \eta_{HCM}\left[\gamma^4 q^2 < \dot{v}_y^2 > /(6\pi\varepsilon_0 c^3)\right] \quad [MKS]$$

with

$$\eta_{HCM} = \left(\lambda_r / \sqrt{2\pi}\sigma_B\right)^2$$

$$(N_{COH}/N_{SP}) \cong N_e \eta_{HCM} \ (>> 1),$$

in practical units,

$$(N_{SP} \cong 7.61 \mathrm{x} 10^{-3} N_e K_R^2 N_R),$$

$$P_{COH}\,[W] \cong 1.585 \mathrm{x} 10^{-14} \eta_{HCM} (\gamma^2 N_e B_R[T])^2$$

- **design example:**

- assume dispersion section

$$L_D\left(1+\left(K_D^2/2\right)\right)=\lambda_u(\gamma/2\Delta\gamma)$$

- then estimated compression is:

$$\frac{\Delta_{\min}}{\lambda_r}\approx\frac{\gamma}{\Delta\gamma_{IN}}\sqrt{2\pi\sigma_\varepsilon^{\;2}+\frac{\left(\pi\left(\sigma_V'^2+\sigma_H'^2\right)\right)^2\gamma^4}{(1+K_D^{\;2}/2)}}$$

Table 1. System and radiation output parameters of a HCM ultra-short pulse buncher/radiator. Longitudinal beam profile Gaussian; transverse profile flat.

Ultra-short Pulse Generator Parameters (γ=300; r_b=100 μm; ρ_B=10.6 C/m^3)	
Bunch Charge	1 nC
$\sqrt{2\pi}\sigma_B$	3000 μm
λ_r	4800 Å
λ_u	8 cm
σ_ε	0.1%
σ_V'	0.1mr
σ_H'	0.1mr
K_D	1
L_D	.445 m
$\Delta\gamma/\gamma$	0.05
Δ_{min}	240 Å
K_R	~1
Compression Ratio (Δ_{min}/λ_r)	6 %
480Å Coherent Photons/pulse	7.0x10^9
P_{COH}	0.18 GW

Radiative output of HCM/Bunching vs. "high harmonic" FEL/OK:

- FEL/OK output proportional to square of "bunching factor" η. Typically η~0.2-0.35.
- For linear-profile HCM, η~1. => HCM output power can exceed FEL's by $1/\eta^2$.

R&D: beam modulation

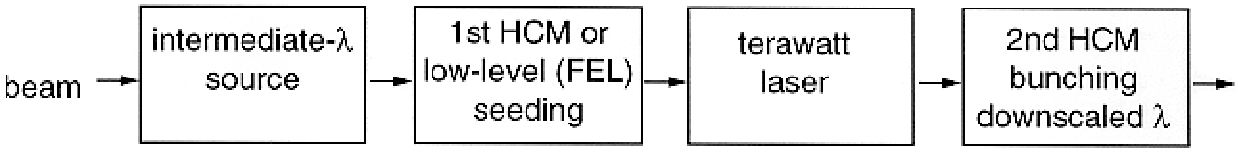
- **high-brightness, low emittance beam development:**
  - no lasing "threshhold" vis-à-vis FEL => wider range of parameters
  - ultra-low energy spread is of primary interest (e.g., semiconductor cathodes)

- **lasers:**
  - reliable higher-power devices (=> petawatt)
  - shorter wavelengths
  - temporal/spectral, spatial/angular control
  - Rayleigh range critical – special optics

- **Field Synthesizers (FSs)*:**
  - control of ($E_l(x,y,z,(t)), B_l(x,y,z,(t))$) critical

- **bunch compression:**
  - $\lambda_r > \sqrt{8\pi\sigma_B}$
  - high-power, high energy (Joule) pulsed microwave sources
  - low-γ beams

- **"bootstrap" seeding/modulation:**
  - modulation linearity
  - bunch parameter control (λ scaling dependent on r_b, ρ_β, <u>and</u> λ_r)



- **HCM theory and simulation**

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*R. Tatchyn, Thursday afternoon, Group 4

R&D: radiation source development

- **single-bunch (ultra-short pulse) sources**
  - can approximate to with transform techniques + non-linearity

- **multi-bunch sources**
  - flexible modulation (FEL autoconvolving; HCM cross-convolving)

- **compact short-wavelength sources**
  - multi-cycle laser + single-cycle FS => minimal size
  - multiple HCM seeding or FEL+HCM seeding
  - FEL + alternative short-wavelength XRFEL systems

R&D: metrology:

- **electron beam metrology**
- **photon beam metrology**

SUMMARY:

- technique provides simple method of generating high intensity attosecond pulses in the VUV/soft X-ray range using high-quality sub-GeV electron beams

- viewed as a coherent "macroparticle, the (single-cycle) pulse is << than the FEL cooperation length. It can consequently produce radiation pulses equal to the FEL slippage length by radiating from a field of N_u periods.

- with development of modulation and dispersion techniques, the high-contrast energy modulation source could be designed to produce singly or multiply-bunched beams

- possible development of radiation/FS field bunch compressors as alternatives to conventional chromatic chicane systems

- proposed technique appears straightforward to implement. Experimentally, the necessary components are: 1) a high power ultra-short-pulse laser, 2) a high quality, high-current electron beam (>25 MeV), and 3) a Field Synthesizer

- potential for size and cost reduction of future generation short wavelength sources

- frontier theoretical and numerical R&D. Electron-beam, laser, and insertion device R&D. Development of experimental and metrological techniques for photon and electron beams

FREE-ELECTRON RADIATION SOURCES BASED ON HIGH-CONTRAST ENERGY MODULATION OF ELECTRON BEAMS*

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ABSTRACT

High-contrast energy modulation (HCM) of electron beams by high-power IR/visible/UV lasers can be achieved when the vector potential of the laser field (Kr) becomes comparable to that of the insertion device (Ku). Detailed theoretical studies of this parameter regime, conducted over the last several years [1,2,3] indicate that practical HCM configurations could be implemented with currently-available terawatt lasers [4], high-brightness electron beams in the 100+ MeV range [5], and low-intensity magnetic field synthesizers [6]. In this talk the basic physics of HCM and bunching, including simulations of collective dynamics in warm beams, will be briefly summarized, and a general comparison of HCM with FEL and Optical Klystron (OK) systems, including their radiative properties, will be presented. Selected novel directions for HCM research, in particular future-generation light source development, as well as possibilities toward reducing the size and cost of short-pulse X-ray FELs, will be introduced for workshop evaluation.

[1] R. Tatchyn, "Quantum Limited Temporal Pulse Generation," Proceedings of the Workshop on Fourth Generation Light Sources, M. Cornacchia and H. Winick, eds., SSRL Report 92/02, p. 482.

[2] R. Tatchyn, "Particle beam modulation techniques for the generation of subfemtosecond photon pulses in the VUV/soft X-ray range," NIM A 358, 56(1995).

[3] R. Tatchyn, "Principles of High-Contrast Energy Modulation and Microbunching of Electron Beams," presented at the FEL'98 Conference, Aug. 17, 1989, Williamsburg, VA; to be published in Nucl. Instrum. Meth., 1999.

[4] C. Le Blanc, E. Baubeau, F. Salin, J. A. Squier, C. P. J. Barty, C. Spielmann, "Toward a terawatt-kilohertz repetition-rate laser," IEEE Journal of Selected Topics in Quantum Electronics 4(2), 407(1998).

[5] J. F. Schmerge, D. A. Reis, M. Hernandez, D. D. Meyerhofer, R. H. Miller, A. D. T. Palmer, J. N. Weaver, H. Winick, D. Yeremian, "High brightness photoinjector development at the SLAC gun test facility," Nucl. Instrum. Meth. A407, (1998).

[6] R. Tatchyn, "Fourth Generation Insertion Devices: New Conceptual Directions, Applications, and Technologies," Proceedings of the Workshop on Fourth Generation Light Sources, M. Cornacchia and H. Winick, eds., SSRL Report 92/02, p. 417.

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