Atto-Second Electron Beam Generation and Characterization Experiment at the ATF

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Motivation

Atom at rest

Atom affected by a slowly varying external field
Motivation

Real electron pulse has shot noise fluctuations

Ionization losses are due to fluctuations that are responsible for high frequencies in the spectra, i.e., frequencies that are comparable with $\omega_{\text{ioniz}}$

Therefore:

$\delta P \sim \sqrt{N}$

$\delta E \sim N$

$\omega_1, \omega_2, \omega_3$ are atomic transition frequencies

Total number of particles in the bunch
Motivation

Short pulses

$E(t)$

$\tau < \omega_0^{-1}$

$\omega_0, \omega_1, \omega_2$ are atomic transition frequencies

Now a collective field of all electrons in the bunch can drive the atomic electron. Therefore:

$\delta P \sim N$

$\delta E \sim N^2$

Transverse limitations:

$\sigma_\perp \frac{c}{\gamma} < \tau$
Optimal condition for interaction

Simple model for media

\[ \epsilon - 1 = \frac{\omega_p^2}{\omega_0^2 - \omega^2} \times 4 \pi n r_e c^2 \]

For short pulse \( \frac{1}{\tau} \approx \omega > \omega_0 \) medium behaves like plasma and compensates electric field of the bunch

For Gaussian beam

\[ N_m^* = \left( \frac{d_{nm}}{\varepsilon a_B} \right)^2 \frac{N^2}{16} \frac{a_B}{\varepsilon_{tr}} e^{-\omega_{nm}^2 \tau^2} \rightarrow 4 \times 10^9 \]

field in vacuum \( E(r) \)

\( 10^8 \text{ V/cm} \)

field in media

\( k_p \sigma_{tr} = 1 \)

\[ E(r, \tau) = \frac{2 q N e^{-\frac{t^2}{2 \tau^2}}}{\sqrt{2\pi c\tau r}} \left( 1 - e^{-\frac{r^2}{2 \sigma_{tr}^2}} \right) \]

\( r / \sigma_{tr} \)
Electric field of coherent transition radiation very similar to collective field of the bunch (virtual photons became real)

This kind of set up can be used for pump probe type of experiments Using X-Rays as probe opens the way for measurement of radial atomic wave functions
Method

Laser: 5mJ per pulse

Photocathode gun: Mg cathode

Electron bunch: 0.5 nC, 5ps, 25 keV, 2 mm-mrad

Undulator parameter

\[ \xi = \frac{K^2 / 2}{1 + K^2 / 2} \]

\[ (\Delta \gamma)^2 = 32\pi \frac{P}{P_0} M \xi \left[ J_0(\zeta / 2) - J_1(\zeta / 2) \right]^2 \]

number of undulator periods

8.7x10^9 W

end station

e-beam-light interaction in the undulator

laser peak power

Bessel functions
Method

Estimate: $\delta E = 0.6$ MeV for $P = 10$ MW, $K = 1.28$, $M = 55$

Simulations (GINGER was used)

Longitudinal phase space at the exit of the undulator.
Modulation amplitude = $40 \sigma_e$

Histogram of electron longitudinal density

Longitudinal phase space at the End Station

cut out with masks

$\sigma = 55$ as
The feasibility of electron pulses of ~100 attosecond is demonstrated.

This attosecond electron pulses will open the way to a new class of experiments based on the interaction of atomic electrons in the medium with the collective electric field of electron bunch, this includes, for example the measurement of the wavefunction of atoms, or coherent ionization losses that are proportional to the square of the number of electrons in the microbunch.
Results

Particle tracking without errors and without cut of tails

Particle tracking without errors and with cut of tails

\[ \sigma = 5.5 \text{ as} \]

\[ \sigma = 120 \text{ as} \]
Results for the ATF beam
Why Atto-Second Pulse at the ATF

• Both LBNL and BNL has long a tradition in IFEL R&D.

• The electron beam quality.
• The laser system.
• Most other hardware available with minimum investment.
ATF Nd:YAG Laser - functional units and beam path

To ATF experimental hall
Hardware now available

The VISA Undulator Section

- **Period length**: 18 mm
- **Number of periods**: 55 segment
- **Magnetic gap** $g$: 6.0 mm
- **Maximum $B$ field $B_{\text{max}}$**: 0.75 T
- **$B$ field error $D B_{\text{max}}$**: 0.4%
- **Undulator parameter $K$**: 1.26
Hardware now available
Coherent Transition Radiation

\[
\rho(x, y, z) = \frac{eN \exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2} - \frac{z^2}{2\sigma_z^2}\right)}{(2\pi)^{3/2} \sigma_x \sigma_y \sigma_z} \left[1 + \sum_{n=1}^{\infty} b_n \cos(nk_r z)\right]
\]

\[
U_n = \frac{N^2 e^2 b_n^2}{8\sqrt{\pi} \sigma_x \sigma_y \sigma_z} \left(\frac{\gamma}{nk_r}\right)^4 \left(\frac{1}{\sigma_x^2} + \frac{1}{\sigma_y^2}\right)
\]
Work need to be done

• New vacuum chamber for the undulator.
• Design match laser transport line.
• Installation.
Schedule

If the proposed experiment approved:
1. funding?
2. New single-shot spectrometer?
3. Design and construction of the undulator vacuum chamber and support. (March - June, 2002)
4. Tuning the undulator. (April - June, 2002).
5. Vacuum testing. (August)
8. Beam time request: 5 runs, each run 2 to 3 days
Summary

• Attosecond Physics
• High Harmonic IFEL.
• High harmonic generation.
• CSR.
• New beam diagnostics techniques.

When such pulses become available, a new vista of applications will appear and add new vitality to the community.