Laser Manipulation of the e- Beam

Alexander Zholents, LBNL

- ESASE & synchronization
- few-cycle modulation & attosecond x-rays
Light interaction with relativistic electron *)

Energy modulation of electrons in the undulator by the laser light

Electron trajectory through undulator

Magnetic field in the undulator

FEL resonance condition

\[ B = B_0 \sin(k_u z) \]

While propagating one undulator period, the electron is delayed with respect to the light on one optical wavelength

\[ \lambda = \lambda_u / 2\gamma^2 \]

*) Motz 1953; Phillips 1960, Madey 1971
The area of the electron bunch with enhanced peak current reaches saturation earlier and produces the dominant radiation.
• The FEL output is dominated by the radiation coming from the part of the electron bunch affected by the laser

More uniform x-ray output one can obtain using modulating laser pulse with a flat top
Absolute synchronization of the x-ray pulse to the pump laser source

Laser pulse arrival time, $t^*$ → pump laser pulse

e-bunch

$t^* - \Delta t_2$  $t^* + \Delta t_1$

Electron bunch arrival time jitter relative to laser pulse $\sigma_{\Delta t} \sim 50$ fs

But, will always be aligned in time

Absolute synchronization of the x-ray pulse to the pump laser source

Laser pulse

Peak current enhancement

X-ray pulse

will always be aligned in time
A schematic of the LCLS with ESASE

**New elements**

- **Laser:**
  - Wavelength: 800 nm
  - Pulse width, FWHM intensity: 20 fs
  - Rayleigh length: 35 cm ($w >> \sigma_x$)
  - Pulse energy: up to 0.5 mJ

- **Wiggler:**
  - Period: 25 cm
  - Number of periods: 9
  - Wiggler parameter, $K=31.5$
  - Peak magnetic field: 1.35 T

**Existing elements**

- Linac 0:
  - Length: 6 m
  - RF phase: $\phi_{rf} \approx -25^\circ$

- Linac 1:
  - Length: 9 m
  - RF phase: $\phi_{rf} \approx -25^\circ$

- Linac 2:
  - Length: 330 m
  - RF phase: $\phi_{rf} \approx -41^\circ$

- Linac 3:
  - Length: 550 m
  - RF phase: $\phi_{rf} \approx -10^\circ$

- BC 1:
  - Length: 56 mm
  - Radius: $R \approx 39$ mm

- BC 2:
  - Length: 56 mm
  - Radius: $R \approx 25$ mm

- DL 1:
  - Length: 6 mm

- DL 2:
  - Length: 0 mm

- Undulator:
  - Length: 130 m

- chicane

- 14.1 GeV
  - Energy: $E = 14.1$ GeV
  - Length: $L \approx 130$ m

**System parameters**

- Beam energy spread: $\sigma_x \approx 0.02$ mm

**Diagram details**

- Synchronization: need isochronous DL 2 beam energy spread

- Laser: wavelength: 800 nm, pulse width FWHM intensity: 20 fs, Rayleigh length: 35 cm ($w >> \sigma_x$), pulse energy: up to 0.5 mJ

- Wiggler: period: 25 cm, number of periods: 9, wiggler parameter, $K=31.5$, peak magnetic field: 1.35 T
Pump-probe experiment concept

Laser excitation pulse

X-ray probe pulse

X-ray detector

ion or e− detector

sample

x-rays

isochronous bend

one period wiggler

wiggler radiation, ~0.5 GW

Near IR pump

After “fact” time jitter measurement between laser pump and x-ray probe

bunched at optical wavelength

• Control/measure of Δt with a resolution better than 100 attoseconds is desirable

LCLS

second harmonic correlator

x-rays
Gain length*)

\[ \lambda = 1.5 \text{ Å, emit} = 0.6 \text{ μm, } \sigma_E = 0.01\% \]

\[ \lambda = 0.5 \text{ Å, emit} = 0.4 \text{ μm, } \sigma_E = 0.01\% \]

*) Ming Xie formulas

Taper should be used to compensate energy chirp induced by space charge,

Note \( I_{\text{peak}} \sim 20 \text{ kA} \)
Energy gradient can be matched with undulator taper to provide the dominance of the radiation from selected group of electrons –
a different way to tied up x-ray signal to the modulating laser

*) Saldin, Schneidmiller, Yurkov
Problem with the slippage of the radiation with respect to the electron pulse

SASE: saturation requires ~ 1000 undulator periods:

a) Slippage length for hard x-rays, i.e. $\lambda = 0.1 \text{ nm}$

$$1000 \times 0.1 \text{ nm} = 100 \text{ nm} \rightarrow 330 \text{ asec}$$

b) Slippage length for soft x-rays, i.e. $\lambda = 1 \text{ nm}$

$$1000 \times 1 \text{ nm} = 1000 \text{ nm} \rightarrow 3.3 \text{ fs}$$

This is about one period of the modulating laser
Single cycle optical pulses and attosecond x-ray pulses
Attosecond pulse generation via electron interaction with a few cycle carrier-envelope phase stabilized laser pulse

Basic idea:
Take an ultra-short slice of electrons from a longer electron bunch to produce a dominant x-ray radiation

Small jitter in the electron bunch arrival time is not important – good for pump-probe experiments using variety of pump sources derived from initial laser signal
Enabling technology

\[ E(t) = E_a(t) \cos(\omega_L t + \varphi) \]

Cosine waveform \( \varphi = 0 \)

Sine waveform \( \varphi = \pi/2 \)

\[ T \tau_0 \approx \frac{6.25}{\lambda_0} \approx 2.5 \text{/fs} @ \lambda_0 \approx 0.75 \mu\text{m} \]

Requires measurement & control of \( \varphi \)
Energy modulation produced in the electron bunch during interaction with a ~1 mJ, 5 fs, 800 nm wave length laser pulse in a two period wiggler magnet with $K$ value and period matched to FEL resonance at 800 nm.
Possible implementation at LCLS

1) CEP laser pulse: $L=800$ nm, 1 mJ, 5 fs

2) One period wiggler $\lambda=80$ cm

3) Bunching and diagnostic chicane

Fourier transform limited and spatial coherent x-ray pulse

$\lambda = 0.15$ nm

$10 \mu$J, $10^{10}$ph, 250 asec
Lasers can play a major role at the LCLS

• assist in synchronization for pump-probe experiments

• enhance peak x-ray power

• assist in generation of attosecond x-ray pulses

What is needed?

• laser, up to 50 fs and up to 0.5 mJ, 120 Hz + wiggler, 9 periods, period length 25 cm

• CEP laser, 5 fs and up to 1 mJ, 120 Hz + wiggler, one period, period length 80 cm
Thank you for your attention