An RF Photocathode for a Recirculating Linac-based Ultrafast Dynamics Facility

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LBNL

Workshop on Laser Issues for Electron RF Photoinjectors
SLAC
October 2002
An ultrafast x-ray science facility for time-domain dynamics experiments

- Repetition rate: 10 kHz
- Synchronization of x-ray pulse to optical pump laser pulse: ≤ 100 fs
- Broad photon range: ~ 0.02 - 12 keV
  - Hard x-rays
    - Tunable: 1 - 12 keV
    - Pulse duration: ≤ 100 fs
    - High flux: up to \(10^7\) (ph/pulse/0.1%BW)
  - UV and Soft x-rays
    - Tunable: ~ 20 - 1000 eV
    - Pulse duration: 200 fs from FEL, ~ ps from spontaneous emission
    - Variable flux: \(10^8 - 10^{10}\) (ph/pulse/0.1%BW)

"Outsider's" view of laser issues for ultrafast dynamics synchrotron radiation facilities

Work in progress

Parameters in red are determined (or strongly influenced) by the photocathode laser system.
Recirculating linac facility for time-domain dynamics experiments

• 10 MeV high brightness RF photocathode gun
• 110 MeV injector linac
• 600-700 MeV superconducting main linac
• Photon production at 2-3 GeV
Synchronize systems to allow controlled delay between pump laser pulse and x-ray pulse
Synchronize seed laser, pump lasers, and electron beam for FEL's

HGHG FEL principle

200 fs seed pulse from Master Oscillator

Position of optical pulses in electron pulse

Low $\varepsilon$ electron pulse

Unperturbed electrons

$\sigma_E \sim \sigma_{E_0}$

Micro orbit-bump (~100 $\mu$m)

Master Oscillator pulse $T_{\text{bunch}} \gg T_{\text{MO}}$

FEL amplifier $L_W < L_{\text{SAT}}$

3rd - 5th Harmonic radiator $P_{\text{HG}} \sim P_{\text{MO}}$

3rd - 5th harmonic FEL amplifier $L_W < L_{\text{SAT}}$

3rd - 5th Harmonic radiator $P_{\text{HG}} \sim P_{\text{MO}}$

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Synchronize deflecting cavities and pump laser for hard x-ray production

RF deflecting cavity

LASER OSCILLATOR (passively modelocked)

3.9 GHz (RF Kick)

laser pulse

electron bunch

x-rays

Timing jitter results in position jitter of compressed x-ray pulse

Undulator

Tail trajectory

~100 $\sigma_r$

Head trajectory

Asymmetrically cut crystal

Early bunch

Synchronous bunch

Late bunch

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Short-pulse laser systems are an integral component of the facility.
Lasers play critical roles in facility

- Time-resolved pump-probe experiments to investigate structural dynamics on fundamental timescale of atomic motion
- Temporal resolution required < 100 fs
  - X-ray pulse duration
  - Laser pulse duration
  - Timing synchronization between beamline pump laser, electron beam, FEL seed laser, and ultimately the x-ray pulse

Highly stable timing system is critical to achieving required temporal resolution

- Overall machine timing determined by a modelocked laser oscillator
- Beamline endstation lasers locked to or amplify the master oscillator pulses
- This oscillator will also be the source of all RF signals for the facility
  - 1.3 GHz RF gun
  - 3.9 GHz linearizing cavity
  - 3.9 GHz deflecting cavities
Laser master oscillator

- Passively modelocked femtosecond laser cavity
  - $< 100$ fs optical pulses
- Phase-lock laser cavity to RF oscillator for long-term stability
  - Cavity acts as VCO by modulating cavity length with a piezo-mounted mirror
  - Phase noise matches RF generator DC to $\sim 1$ kHz, substantially better at higher frequencies
- Highly-stable comb generator is source of all RF signals by use of photodiode
  - 1.3 GHz ($16 f_0$)
  - 3.9 GHz ($48 f_0$)

<table>
<thead>
<tr>
<th>Master Oscillator Laser</th>
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<tbody>
<tr>
<td>Pulse duration (fs)</td>
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<tr>
<td>Wavelength (m)</td>
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<tr>
<td>Repetition rate (MHz)</td>
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<tr>
<td>Average power (W)</td>
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</table>
• Master oscillator laser pulses are distributed via an optical transport system
  - To beamlines
  - To the photocathode laser
  - To FEL seed lasers

• Pulses may be amplified at the beamline

• Beamline laser may be synchronized to the master oscillator
Transport system must be highly stable
- Path length drift 10 µm = 30 fs
- Free propagating beams and mirrors
- Hermetically sealed optical transport systems
- Active positioning system

or
- Fiber delivery system
- Low pulse energy avoids non-linear effects
- Photonic band-gap fiber may control dispersion
- 1.55 µm master oscillator could take advantage of zero-dispersion fiber
Delay lines and path lengths

- Need flexible delay to match the path length of the laser pulse and the x-ray pulse at each beamline endstation
- Optical delay kept to minimum to preserve stability
- Master oscillator is extremely stable delay
  - Beamline users can select any pulse from the 81.25 MHz train of pulses
  - 12.3 ns pulse separation

- Stability over time period of the required delay
  - ~ 10 µs
  - 10 µs corresponds to ~ 812 round-trips in the master oscillator
  - For timing accuracy of 30 fs, the path length variation in this time must not exceed 10 µm
    - 0.012 µm per round-trip
  - 12 nm in 12.3 ns
    - ≈ 1 ms⁻¹
  - Requires force beyond that generated from acoustic disturbances or piezoelectric transducer
RF photocathode parameters

- Energy: 10 MeV
- Charge: 1-3 nC
- Normalized RMS emittance: $3 \ \pi \text{mm-mrad}$
- Energy spread at 10 MeV: $\pm 15 \text{ keV}$
- Pulse length: 20 ps
- Repetition rate: 10 kHz
- RF frequency: 1.3 GHz
- Peak E field on a cathode: 64 MV/m
- Cathode material: Cs$_2$Te
- Laser wavelength: 260 nm
- UV pulse energy at cathode: 10 $\mu$J
- Pulse length (FWHM): 20 ps
- Laser spot radius: 1-2 mm
Lock cavity RF systems to laser master oscillator

~ 0.01° phase stability feasible
1.3 GHz RF gun and scrf linac
(similar for 3.9 GHz scrf)
Photocathode drive laser

- $\text{Cs}_2\text{Te}$ cathode surface
  - Quantum efficiency $\approx 1\%$
  - 0.26 $\mu\text{m}$ laser matches work function of 4.64 eV
  - 1 nC requires $\approx 0.5 \mu\text{J}$ per pulse

- Nd:YLF or Nd:YAG oscillators available (Time-Bandwidth GE-100 series)
- Phase-lock to master oscillator
- Regenerative amplifier (Positive Light)
- Frequency quadruple

\[
W_{\text{laser}} = \frac{Q_{\text{bunch}} \cdot \frac{hc}{e}}{\text{Q.E.} \cdot \lambda_{\text{laser}}},
\]

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<td>Repetition rate (kHz)</td>
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<tr>
<td>Pulse energy @ 0.26 mm (J)</td>
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</tbody>
</table>
Photocathode drive laser

• Rise/fall time
  - ~ 2 ps (Ti:sapphire or glass may be required for ≤ 2 ps)

• Generate 20 ps pulse
  - Acousto-optic pulse shaper

• Amplitude stability
  - ~ 1 %
  - Clip

• Spatial profile and stability
  - Uniform distribution over 2 mm radius
  - Deformable mirrors
  - Avoid thermal lensing
  - Cryo-cool crystal
  - Pinhole
YAG / YLF laser

The Series GE-100 is a passively mode-locked, diode-pumped picosecond laser system using semiconductor saturable absorber mirrors (SESAMs). This new approach to picosecond pulse generation offers several distinct advantages compared to established technologies such as active/passive mode-locking.

Passive mode locking: The GE-100 employs TFBS's patented SESAM technology which provides unprecedented stability and self-starting reliability in mode-locked lasers. The laser begins pulsing at turn on and reaches its specified performance within seconds to minutes.

All-solid-state design: The combination of a semiconductor pump laser and saturable absorber yields very clean picosecond pulses with exceptional amplitude and phase noise performance. The "Gain-And-The-Loss" SESAM design maximizes band-with due to enhanced spatial hole burning which also contributes to shorter pulses within the excess of an increased time-bandwidth product. We achieve parameters typically two times shorter than actively mode-locked systems.

Ease of use: Passive mode locking means turn-on is typically less than one minute. Dedicated diagnostics such as an autocorrelator are not necessary. A built-in noninterfering power meter or a power meter head is optionally available. The power supply requires standard wall-plug voltage only, and both laser head and supply require simple connect at power on. Resulting in easy installation and low operating costs.

Expandable: The GE-100 is a compact tabletop laser system. It can also be configured for applications such as user specified repetition rates ranging from 25 kHz to 1 GHz. Enhanced pulse energy/pulse energy is available for applications requiring an adjustable frequency doubling and third harmonic generation, or a user-selected narrow or broad spectrum. The GE-100 can also be integrated with the optional frequency-doubler feedback system CLX-1100. We also provide optimized, compact systems for OEMs or other specialized applications.

Technical specifications:

- Wavelength: 1064 nm
- Pulsewidth: 4 ps
- Repetition rate: 100 MHz
- Input power: 800 mW
- Operating temperature: 15°C to 35°C
- Storage temperature: -20°C to 70°C
- Relative humidity: 10% to 90%
- Cable length: 5 m
- Laser head dimensions: 31 x 16 x 63 cm
- Power supply: 21 x 11 x 63 cm

Options (please inquire):

- User specified pulsed power from 100 ps to 300 ps available
- User specified repetition rates from 25 MHz to 1 GHz
- Synchronization option: Mode CLX-1100 timing stabilizer feedback system
- Available option XHP-3 / XHP-6: average power 3W or 6W at 1064 nm (please inquire for quote)

OEM Systems:

We provide optimized, compact systems (such as the Lynx) for OEM applications. Please contact us with your requirements.

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## Temporal pulse shaping

### Technical Specifications Dazzler 800 / 1.0

#### Optical characteristics
- Central optical wavelength: 800nm
- Bandwidth: 200nm
- Interaction length: 25mm
- Maximum diffraction efficiency: >50% (100nm bandwidth signal)
- Maximum programmable delay: 3 ps
- Damage threshold: 100MW/cm²
- Acousto-optic module dimension: 50mm x 90mm x 20mm

#### RF Generator
- Central frequency: 52.5MHz
- Bandwidth: >10MHz
- Dynamic range: >50dB
- Acoustic signal duration: 58µs or less
- Acoustic signal repetition period: 58µs
- Dimensions: 560x130x300mm³

#### Programmable acoustic waveforms
- Fixed frequency sinusoid (amplitude and duration control)
- Frequency chirped sinusoid
- Polynomial complex spectrum (phase and amplitude control)
- Arbitrary complex spectrum within bandwidth limits (from disk file)

#### Synchronization characteristics
- Trigger Signal amplitude: TTL in 50 Ohms
- Trigger Signal width: >10ns
- Trigger delay adjustment precision: 100ns
- Trigger delay adjustment range: 58µs

#### Programming computer
- Laptop
- USB interface to RF signal generator

#### Power supply
- 110/230V 150W.

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**DAZZLER™**

Acousto-optic programmable dispersive filter (AOPDF)

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Amplifier

- Hurricane®
  - Hurricane provides 1 mJ at 1 kHz with sub-130 fs pulse duration.
  - Excellent beam quality
  - Unmatched energy stability (< ±1.5% peak-to-peak)
  - All computer controlled
  - Small footprint (2 ft by 3 ft)
  - Minimum utility requirements (110/220 V single phase and no external water)
  - Only all solid-state amplifier system patented
  - High energy output at 1 kHz
  - Excellent energy stability (< ±1.5% peak-to-peak)
  - Near Gaussian, near diffraction-limited output beam
  - Near transform limited output pulses
  - Beam Diameter: 5 mm (nominal)
  - Transverse Mode: TEM00 1.5x diffraction limit
  - Repetition rates of 1-5 kHz. Higher repetition rates are available on a custom basis
  - High pre-pulse and post-pulse contrast ratio
  - Pre-pulse Extinction Ratio: >1000:1 (1 kHz), >500:1 (5 kHz)
  - Post-pulse Extinction Ratio: >100:1
Summary

• Time-resolved pump-probe experiments to investigate structural dynamics on fundamental timescale of atomic motion
  - Temporal resolution required < 100 fs

• Highly stable timing system is critical to achieving required temporal synchronization between x-ray and laser pulses

• Overall machine timing determined by a modelocked laser oscillator

• Photocathode laser demanding but appears feasible

What are realistic parameters for operational, integrated systems?