LDRD PROPOSAL

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Summary of Proposal

Description of Project

The LCLS promises to be the premier source in the world to capture the molecular action of a chemical reaction "frame by frame". The technique used to film this molecular movie is the pump-probe technique where a femtosecond optical laser is used to trigger the reaction and the LCLS X-rays probe the femtosecond response. In the fullness of time, all LCLS instruments will utilize this technique.

The most significant challenge associated with capturing a molecular movie is to time the optical pump pulse with the probe pulse with sufficient precision to not "blur" the images. This requires either controlling the time delay to a value that is a fraction of the LCLS pulse duration (10's of femtoseconds) or measuring the timing on a shot-by-shot basis and processing the data accordingly.

Presently, the timing of the pulses can be controlled to within ~200 fs FWHM and thus the resolution of time resolved experiments is limited to this value. This value isn't expected to improve significantly in the near or far term of the facility for various reasons. However, it is now feasible to develop a diagnostics to measure the relative timing with the desired precision.

We propose to directly measure relative time jitter of X-ray and pump laser pulse near the sample using a cavity excited by X-ray-pulse photoelectrons. A similar approach is used to measure relative timing of electron bunch and rf reference in accelerators, where a short electron bunch excites electromagnetic fields in high Q, multi GHz rf cavity and the rf phase of the decaying signal is compared to a reference.

The device can be located just before the sample to non-invasively monitor the relative timing of X-ray and pump laser pulse. The development will include simulations of the X-ray/target interaction, electron beam dynamics, electrical and mechanical design of the cavities, their manufacturing, design and commissioning of detector's electronics, and testing with the X-ray beams. This project will fully benefit from the unique SLAC expertise in beam simulations, design of precision RF structures, precision electron beam diagnostics and also merges the efforts of the PPA division (Acc. Tech. Research/ARD) and LCLS.

Expected Results

The development of this device will allow femtosecond measurements of the X-ray/laser pulse timing. Such a diagnostic is a mission critical tool for the LCLS and is required to reach the facilities advertised performance.

Proposal

One of the many technical challenges in LCLS operations for users is the measurement of X-ray pulse timing and specifically, for pumps probe experiments, the time difference between optical laser pulses and X-ray pulses. Timing jitter between the optical probe and the electron bunch could be measured with 20 fs resolution using an electro-optic sampling device at the exit of the last undulator, but then the X-ray pulse is separated from the beam and has to travel hundreds of meters to reach the experimental sample. This large distance makes measurement of the X-ray pulse timing difficult.

Similar problem of synchronization of a very short electron bunch and GHz rf fields exists in accelerators. It is solved using a "beam-phase-monitor" (see for example R. Akre, V. Pacak, "LCLS Beam Phase Cavity", 2006, http://www.slac.stanford.edu/grp/lcls/controls/global/subsystems/llrf/Phasing

Cavity_ESD_04_24_06.pdf). In this monitor, the electron bunch passing through the cavity excites the cavity's resonant modes. One of these modes, usually the fundamental, is coupled to an outside circuit where the signal from the mode is mixed with a reference rf signal. The phase of the downmixed signal is measured relative to the phase of an rf reference. The typical accuracy of this measurement for multi GHz signals is about a degree. One degree for 11 GHz signal is 0.25 ps and for 30 GHz signal 90 femtoseconds.

We propose to extend this approach to detect the timing jitter between the LCLS X-ray pulse and the femtosecond optical laser. We suggest improving timing resolution using "null" measurements. We will create two rf signals of close frequencies and decaying with the same rate. One signal will come from the rf cavity excited with X-ray beam, another from rf cavity excited by signal from a photodiode (the photodiode detects pulse from pump-probe laser). Both signals will be combined in a passive 3dB hybrid and then phase and amplitude of the subtracted signal will be measured (the sum signal form the hybrid is also detected). We expect the short-time (over minutes) resolution of the device's circuit to be few femtosecond.

When the X-ray pulse hits a 100 nm layer of Aluminum deposited onto a Si_3N_4 membrane, an electron bunch comes out of the target and excites the fundamental mode of the cavity. A schematic view of the cavity is shown in Fig. 1. Currently we are considering a 10-30 GHz cavity with copper Q value of 2000…6000. The field excited by the bunch is coupled out of the cavity. At the same time a laser pulse hits a photodiode and the resulting signal is filtered through another rf cavity with loaded Q matched to that of the cavity with X-ray target. We show a possible circuit on Fig.2. The rf signals with similar decay times are amplified with a low noise amplifier and then combined using a passive hybrid. Signals from both sum and difference outputs of the hybrid are subsequently downmixed to 100…500 MHz. Then the low-frequency signals are digitized and analyzed. We anticipate this system to work shot-to-shot with repetition rates up to a kHz (LCLS operating repetition rate is 120 Hz). We expect that the "null" measurement using "passive hybrid-active mixer" combination will allow measurements of rf phases with sub-degree resolution, which will translate into 10s of femtoseconds in timing for "ideal" rf signals. Because of this high resolution of the rf circuit, we think that the precision of the whole device will be determined not by the rf circuit but by ability of X-ray target to produce accurate time-replica of the X-ray beam.

To determine practical resolution of the device, we may test it in Hutch 3 of the Near Experimental Hall (NEH). We could test the system with the LCLS x-ray beam and NEH laser system on the X-ray Pump-Probe (XPP) instrument.

We propose to design, manufacture and test these time-jitter-detectors for further use at LCLS.

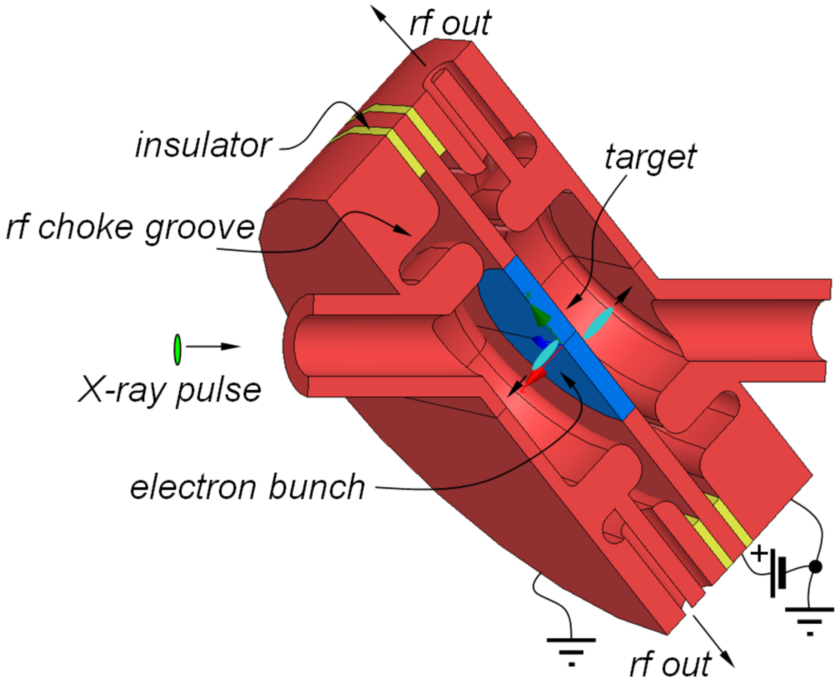

Figure 1: Schematic view of the timing cavity.

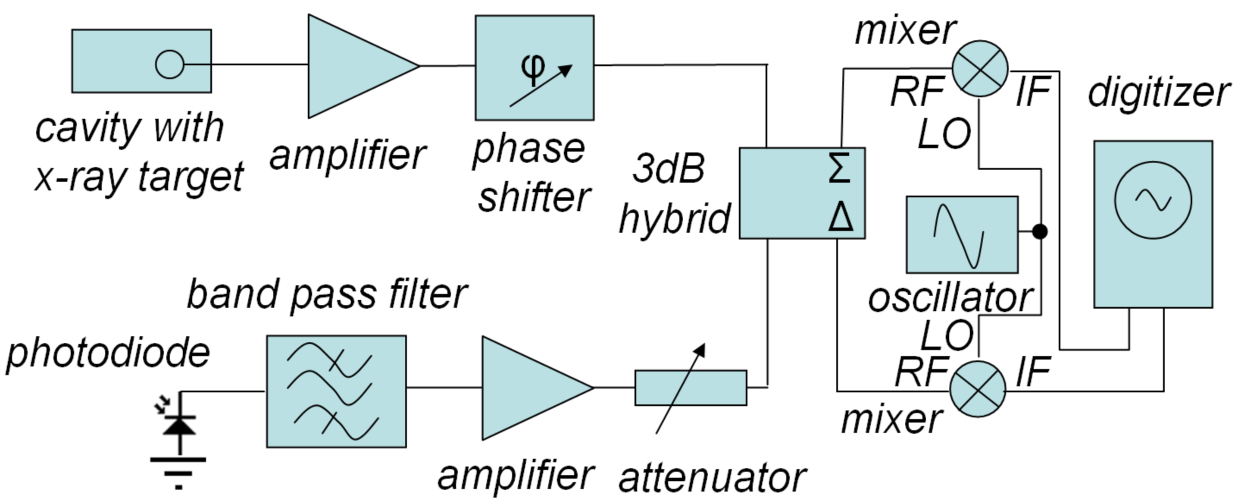

Figure 2: Possible circuit of the timing detector.

Purpose/Goals

We propose to design, build, and test a cavity for measuring the relative timing jitter betweens LCLS X-ray pulses and pulses from pump-laser.

Approach/Methods

Development of the timing detector could be partitioned into several stages:

1. Analysis of X-ray beam-target interaction.
2. Simulation of beams in the cavities.
3. RF design.
4. Mechanical design.
5. Manufacturing.
6. Cold test.
7. Commissioning with X-ray and laser beams.

1. Analysis of X-ray beam-target interaction.

The X-ray beam target, or cathode, is used to excite the cavity using electrons ejected by the X-rays via fundamental processes. These processes include the prompt k-shell photoelectric effect, L-shell photoelectric effect if any, and subsequent secondary radiative or non-radiative processes such as X-ray fluorescence, Auger electrons, and secondary electrons via cascading processes. The k-electrons have energies that are close to that of the incident X-rays, whereas the Auger and secondary electrons are much slower. Since the device will be used in a non-invasive manner, the target material must be made of low-z material to avoid damage and to afford high transmissivity. X-ray fluorescence as well as L-electrons can be neglected compared to the Auger process. Since secondary electrons typically have energies on the order of eV, there are orders of magnitude more secondary electrons than the k-electrons or Auger electrons, and these slow electrons would severely compromise the timing response of the target and must be minimized. The best way to make k-electrons the dominant signal is to make the target extremely thin (on the order of 10 to 100 nm), the same order as the escape depth (or effectively the electron mean free path) so that there will be very little electron-electron scattering. Since the binding energy of low-z materials is small compared to the incident X-ray energy, the k-electrons are quite mono-energetic, and would give rise to a prompt electron sheet charge departing from the surface at speed close of a fraction of speed of light. If the target is grounded or slightly reverse biased to discourage residual slow electrons, it would effectively create an electron beam upon impact of the X-ray beam with a time profile that is set by the sub-femtosecond scale of core-electron's life time.

2. Simulation of beams in the cavities.

Based on results from X-ray-target analysis, we will perform simulations of photoelectron beam dynamics using Particle-In-Cell and beam-dynamics codes like MAGIC and PARMELA. Here we evaluate possible cavity geometries, target biasing options and estimate accuracy of the device's time measurements.

3. RF design

The electrical design of the cavities will be done with in-house and commercial electromagnetic simulation software and will follow procedures we have developed for design of accelerator cavities. Design of the RF measurement system will follow methods used for design of precision rf and particle-beam diagnostics.

4. Mechanical design.
The mechanical design, again, we will also follow procedures developed and successfully used for precision accelerating structures and cavities. This work will be done in the ATR department.

5. Manufacturing.
We propose to build a prototype in the SLAC Klystron Laboratory shops. The Klystron Laboratory has all the necessary skills and equipment to produce high precision and ultra-high-vacuum-compatible prototypes.

6. Cold test.
We will perform cold test of the cavities first, with vector network analyzers and then with pulsed sources to commission the device and measure its characteristics. Similar tests will be done for the detector's electronics. This work will be done in ATR department.

8. Commissioning with X-ray and laser beams
We will test the system with the LCLS x-ray beam and NEH laser system on the XPP instrument.

Specific Location Where Work will be Done

The design, prototype work and cold testing will be carried out in the ATR department and the SLAC Klystron Laboratory. The beam tests will be done at XPP instrument at LCLS.

Anticipated Outcomes/Results

As a result of this project we expect to commission a device that allows femtosecond measurements of the LCLS X-ray pulse timing for use with laser-driven pump probe experiments.

Budget

Scientific labor: 0.6 FTE for 2010

Support labor: 0.2 FTE

M&S: $20k for 2010 (burdened)

Shop: $40k for 2010 (burdened)