A PLASMA ATTENUATOR FOR SOFT X-RAYS IN LCLS-II*

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Abstract

LCLS used a gas column to attenuate soft x-ray pulses by factors of up to 10^5. In LCLS-II, thermal effects from x-ray absorption at high repetition rates will lead to unpredictable attenuation that depends on the spacing and energy of prior pulses. An argon plasma in an RF cavity is presented as an alternative. X-ray absorption then becomes a perturbation compared to the energy deposited from RF excitation. An LCLS-II solid-state RF amplifier, generating up to 5 kW at 1.3 GHz, can provide the drive, and the FPGA-based low-level RF controller can be programmed to track tuning with plasma density. Several diagnostics are planned to monitor plasma properties over a fill-pressure range of 10 to 1000 Pa.

INTRODUCTION

Temporary reduction of the pulse energy of an x-ray FEL beam is often required to prevent damage to critical components, such as highly specialized x-ray detectors, for alignment, or to study x-ray nonlinear effects. An x-ray attenuator allows the user to vary the incident pulse energy in a well-controlled manner without altering other FEL characteristics, unlike other methods such as operating at different points of the FEL gain curve or lowering the electron bunch charge. For soft x-rays, a fully saturated FEL pulse at a typical operating bunch charge of 100 pC would completely damage any solid attenuator located sufficiently close to the FEL source point. Consequently, attenuation in gas has been considered the only viable solution; gas attenuators have been implemented at many facilities around the world, including the Linac Coherent Light Source (LCLS) [1] at SLAC.

At a sufficiently low repetition rate, such as 120 Hz at LCLS, a gas attenuator at room temperature provides an effective attenuation that is simply governed by the Beer-Lambert law [2-4] (relating the gas pressure at a constant temperature to the attenuation length), and is deterministic and independent of the FEL beam parameters. However, LCLS-II will operate at repetition rates up to 1 MHz. With increasing rate, a gas attenuator will begin to exhibit nonlinearities that depend on the FEL pulse rate and energy, along with the thermal diffusivity and absorption cross section of the gas. Even more troubling is the onset of hysteresis: the attenuation of trailing pulses depends on the intensities and arrival times of earlier ones. Such previously unsuspected behavior arises because the energy deposited by an FEL pulse requires a finite time to dissipate, on the order of 1 ms. The original gas density distribution is perturbed, modifying the effective attenuation of the pulses that come during this recovery time.

Here we present the concept of a column of partially ionized plasma in place of the gas, in order to stabilize the attenuation at high repetition rates. The plasma is hotter, and its thermal relaxation is much faster. The energy deposited by a few-mJ FEL pulse would then present only a small perturbation, and the densities of electrons, neutrals, and ions will recover between LCLS-II pulses. The plasma would provide a stable, controllable, and deterministic x-ray attenuator.

ATTENUATION IN A GAS COLUMN

A typical gas-based attenuator for x-ray FEL pulses consists of a few-meter-long gas column, bookended by differential pumping sections to maintain ultra-high vacuum elsewhere along the beamline. Nitrogen and argon are common, inexpensive choices, operating at pressures between 10 and 1000 Pa. Soft x-rays below 1.5 keV can be attenuated by a factor of up to 10^5.

Early in the planning for LCLS-II, concerns about the effect of its high repetition rate led to thermodynamic and hydrodynamic simulations [5,6] of a gas attenuator. It was found that the x-ray energy deposited by photoabsorption would eventually thermalize into the kinetic degrees of freedom of the gas molecules, raising the temperature on axis and reducing the local density to create a “hole” that lasts for a few ms, during which the attenuation of subsequent pulses is reduced.

When the FEL runs at a high but steady rate and pulse energy, a gas attenuator may stabilize, although at a level different from that prescribed by the Beer-Lambert law. However, the pulse energy fluctuations of a SASE FEL cause each pulse to encounter a different gas density distribution. Instead of a true steady state, the distribution depends on the deposited energy and arrival time of earlier pulses, causing hysteresis in the effective attenuation.

Experimental evidence of the density “hole” induced by an FEL pulse was first demonstrated at LCLS using a two electron bunches separated by 123 ns. Each bunch generated a hard x-ray pulse that passed through a test gas cell. The transmission of the second pulse relative to the first increased by approximately 20% [7].

ATTENUATION IN A PLASMA COLUMN

Concept

The fundamental deficiency of a room-temperature gas attenuator operating at high repetition rate stems from its relatively low energy scale of 25 meV/atom, corresponding to a temperature of 300 K. Thermal equilibrium is

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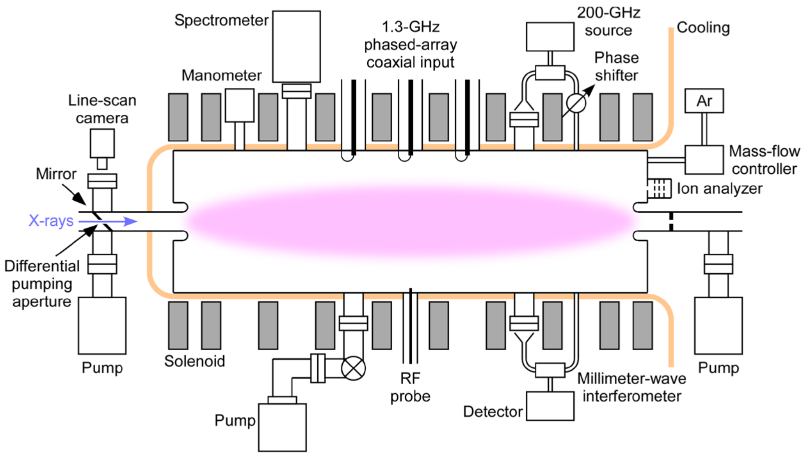

Figure 1: A conceptual design of a plasma-based x-ray attenuator, with the associated pressure controls and plasma diagnostics.

destroyed when the gas absorbs a mJ x-ray pulse and recovers after a thermal relaxation time of a few ms, 1000 times too slow for MHz pulse spacing. In contrast, the plasma electron temperature would be 5 eV, or 60 000 K. The thermalization of fast photoelectrons generated by the x rays becomes a small perturbation to the plasma with minimal impact on the attenuation of subsequent pulses. The plasma can be created and heated by either RF or a DC discharge [8]. In either case, collisions heat the ions and neutrals. RF heating via certain modes (below) offers the further advantage of direct ion excitation.

Consider partially ionized (≈0.1%) argon, with the number density of neutrals n_0 well above that of electrons n_e and ions $n_i = n_e = n$. Compared to ionization, which removes only an outer-shell electron, x-ray absorption ejects a core electron. Because this electron is more tightly bound, ionization should not alter the absorption cross section of an ion compared to a neutral. Consequently, a given attenuation requires the same density for a gas column or for the gas that is ionized to form a plasma column.

Plasma Parameters

In 1889, Paschen found that the minimum electric field to ionize a gas occurs at an optimal pressure [9]. Breakdown requires an avalanche in which the field accelerates a free electron to the ionization energy (15.76 eV for Ar) between collisions. Above the optimal pressure, collisions are too frequent for sufficient energy gain. Below it, in an RF-driven discharge, an electron is unlikely to collide in a period of oscillation. In a DC field, the mean free path exceeds the chamber size, and collisions are again unlikely. This optimal pressure is typically near 100 Pa.

Argon is a relatively easy gas to ionize with RF, requiring a field as low as 400 V/cm at 1 GHz and 130 Pa [10]. Such a field is easily achieved in a resonant cavity of moderate Q. Argon was effective for absorbing x rays in the LCLS gas attenuator and so is well suited for a plasma attenuator. At 100 Pa and 300 K, its mean free path is 70 µm and its density is 2.4×10^{16} cm^{-3}.The collision rate for 5-eV electrons with neutrals is then 13 GHz.

Plasma Diagnostics

Several diagnostics verify the conditions for breakdown and monitor the plasma parameters for suitability and stability. Figure 1 sketches these, grouped around the chamber.

Since heat from the 5-kW RF drive ultimately flows to the chamber walls, they are water cooled. A solenoid provides an axial (z) magnetic field B_s for better electron confinement. For B_s to be helpful, the electron cyclotron frequency should exceed the collision rate; consequently, a field of at least 0.5 T is desirable. The solenoid is also water cooled.

As in the gas attenuator, differential pumping maintains ultra-high vacuum conditions on either side of the plasma chamber. Inside, a mass-flow controller, a capacitance manometer, and a vacuum pump with a throttling valve operate in a control loop to maintain the desired pressure on the periphery of the plasma. Confinement of the RF power does not depend on the pumping apertures, since the diameters of the entrance and exit tubes are below cut-off at 1.3 GHz.

The differential-pumping aperture at the upstream end has a mirrored face and is tilted to give a camera an end-on view of the center of the plasma. A density hole would reduce the intensity on axis when high-rate x rays are present. The effect of the plasma can be tested by reducing the RF drive or the solenoidal field. A line-scan (one-dimensional) camera is preferred to a standard 2D camera for the fast readout (up to 200 kHz), which can highlight plasma breakdown and any change in the plasma emission following an x-ray pulse or pulse train.

Optical spectroscopy provides insights into the excitations of plasma ions versus neutrals. X-ray absorption by an argon ion produces doubly ionized argon (Ar^{++}). For a given plasma density, the ratio of the spectral lines of Ar^{++} to lines of single ionized argon (Ar^{+}) then scales with the energy in the x-ray pulse.

To determine the degree of ionization, a millimeter-wave (200 GHz) interferometer measures the plasma density integrated across the diameter. The phase shift from the plasma's refractive index η is compared to a reference path outside the chamber. Both the interferometer and the camera indicate the stability of the discharge.

The ion analyzer [11], which measures the ion energy distribution, is essentially a Faraday cup with a series of biased grids to reject electrons and to sweep the energy of ions accepted by the cup.

RF Penetration into the Plasma

Consider launching a wave in the y direction at a frequency (see below) $f_{RF} = \omega_{RF}/(2\pi) = 1.3$ GHz. To heat the center of the plasma, the wave must first propagate inward from the wall through a rising plasma density n that strongly affects RF propagation.

The response of electrons or ions to a z-polarized wave is not affected by B_s, and so the plasma's refractive index is the same as that of an unmagnetized plasma, and depends only on the electron plasma frequency ω_{pe}:

$$\eta^2 = 1 - \frac{\omega_{pe}^2}{\omega_{\mathrm{RF}}^2} = 1 - \frac{ne^2}{\varepsilon_0 m_e \omega_{\mathrm{RF}}^2} \quad (1)$$

The wave penetrates into the plasma until it encounters a cutoff ($\eta^2 < 0$). For 1.3 GHz, this occurs at $n = 2.1\times10^{10}$ cm^{-3}, well below that needed for the desired pressure and ionization fraction. There is no resonance ($\eta \to \infty$).

An x-polarized wave can excite a resonance at the "lower-hybrid" frequency ω_{LH} [12], which drives both electrons and ions and depends on the ion plasma frequency ω_{pi}:

$$\frac{1}{\omega_{\mathrm{LH}}^2} = \frac{1}{\Omega_i^2 + \omega_{pi}^2} + \frac{1}{\Omega_i \Omega_e} \quad (2)$$

Here $\Omega_{e,i} = eB_s/m_{e,i}$ are the electron and ion cyclotron frequencies, respectively above and below ω_{RF}. However, the wave is blocked from the resonance by a cutoff at a density (for $B_s = 0.5$ T) of 2.5×10^{11} cm^{-3}, still far too low.

If instead the wave is launched in the yz plane at an angle to y, the cutoff can be avoided [12]. An elliptically polarized wave at an angle of 60° to z can penetrate to a core plasma density exceeding 10^{15} cm^{-3}, where it is strongly resonant. Lower hybrid heating and current drive in fusion experiments launch such angled waves with a phased array of waveguides [13]. The phased array illustrated in Fig. 1 follows this model.

RF Cavity

The plasma chamber will be designed as a resonant cavity that supports the launch of an elliptically polarized 1.3-GHz wave at an appropriate angle to the solenoidal field, to generate and heat the plasma. The cavity will support both the TM_{01} and TE_{11} modes with an electric field on axis of approximately 1.5 kV/cm with 2 kW of applied RF, more than sufficient to ionize 100 Pa of argon [10], with some RF power overhead for cavity control.

The size of a cavity at this frequency is appropriate for an X-ray attenuator, with a length of ≈1 m. Because the argon is primarily ionized where the field is high along the axis and where the solenoid confines the plasma, this arrangement is suited to attenuating x rays on axis.

A similar concept, RF-generated plasma in a resonant cavity, is now routinely used to clean niobium accelerator structures. RF at 1.3 GHz ignites 25 Pa of argon, with a small percentage of O_2 added after ignition to aid in removing hydrocarbons [14]. Wall cleaning benefits from using high-order modes to generate a low-temperature plasma throughout the cavity rather than along the axis.

RF Power and Control

The choice of 1.3 GHz allows us to use common LCLS-II RF hardware, including the 5-kW solid state RF amplifier (SSA). The SSA is designed as a transistor array with RF isolators to protect against reflected power at each transistor output. The array can be reconfigured to drive multiple cavity antennas, each at a different phase.

LCLS uses an FPGA-based low-level RF controller with a high closed-loop bandwidth. With a relatively low field gradient in a low-Q wideband cavity, the tuning range is wide enough to quickly track changes in plasma-loading of the cavity with a self-excited loop algorithm.

SUMMARY AND NEXT STEPS

A gas-based attenuator for a soft x-ray FEL will exhibit unpredictable attenuation and hysteresis at high repetition rates, as the heat deposited by the x rays causes a density depression along the axis. An attenuator based on an RF-driven plasma column can provide a more stable alternative, since the x-ray heat load becomes a perturbation compared to the energy stored in the plasma.

We have proposed a prototype plasma chamber to be built over the next two years, to demonstrate the control of a plasma with the requisite density and stability.

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