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BURST-MODE UV ENHANCEMENT CAVITY FOR LASER-ASSISTED HYDROGEN ION BEAM STRIPPING AT SNS*

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Abstract

Recent success of laser-assisted charge exchange for 10 µs duration Hydrogen ion beams at SNS motivates laser development necessary for efficient stripping of 1.0 ms duration beam at full duty cycle. To overcome the laser power challenge, the interaction point was chosen inside an optical cavity. A doubly-resonant enhancement cavity and a novel locking technique have been developed, and a coherent enhancement of 402.5 MHz, 50 ps, 1.05 MW peak power ultraviolet (355 nm) laser pulses operating at 10-µs/10-Hz burst mode has been demonstrated. This will enable 1.0 ms duration laser macropulses at 60 Hz to be stored inside such a cavity to achieve efficient stripping at SNS.

INTRODUCTION

Following a successful proof-of-principle demonstration [1] using a 10-ns/30-Hz Q-switched laser, a more advanced proof-of-practicality experiment was recently conducted at the Spallation Neutron Source (SNS) [2, 3, 4] using 10-µs/10-Hz burst-mode laser. The final phase of the experiment is to demonstrate high-efficiency full cycle H^- beam stripping at 1-ms/60-Hz at an operational accelerator setting. High efficiency stripping at full cycle imposes many challenges on laser technology. The direct scaling of average laser power to full cycle H^- beam stripping requires laser power of at least 1.2 kW at 355 nm with repetition rate of 402.5 MHz and pulse width of 50 ps. This is beyond the capability of current state-of-the-art burst-mode laser systems. However, since the cross section for the photon-ion interaction in the laser stripping process is extremely small, the stripping event results in a negligible laser power loss ($\sim 10^{-7}$). Thus, the laser power can be recycled and enhanced if the interaction point is located inside an optical cavity.

Enhancement cavities have been widely employed in high harmonic generation [5, 6], THz generation [7], x-/γ-ray generations via inverse-Compton scattering from relativistic electrons [8]. However, laser stripping experiment requires a burst-mode laser with very small duty factors (~6%). In such cases, it is difficult to generate an effective error signal within the short duration of the laser suitable. Recently, we developed a locking technique using a doubly resonant optical cavity scheme to realize cavity enhancement of UV lasers operating in the burst mode [9]. In this paper, we report a coherent enhancement of 402.5-MHz/50-ps, burst-mode UV laser pulses operating at 10-µs/10-Hz with megawatt peak power and a corresponding enhancement factor of ~50 inside the cavity.

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DOUBLY-RESONANT CAVITY LOCKING PRINCIPLE

A principle of the doubly-resonant enhancement cavity (DREC) locking technique is shown in Fig. 1. Two incident beams originating from the same laser can have either the same or different (harmonic) wavelengths. The double-resonance is obtained when the following condition is satisfied.

$$mod\left(\frac{\Delta L}{\lambda}+\frac{\Delta \nu}{FSR},1\right)=0$$

where ΔL is the path length difference, $\Delta \nu$ is the frequency difference of the two incoming beams, FSR is the free spectral range. The double resonance of a cavity to these incoming beams can be realized by properly tuning the frequency difference and therefore phase shift between two beams. The frequency difference between two beams, in this case, can be tuneable up to the free spectral range (FSR) of the cavity. When the double-resonance condition is met, the locking of the cavity can be achieved based on conventional techniques such as Pound-Drever-Hall (PDH). However, the locking scheme uses the slave (auxiliary) beam that has the continuous pulse structure and burst-mode beam must be on resonance in the cavity and both beams must have the constant phase offset. Frequency shift of an incoming laser beam to the cavity can be accomplished by using a fiber pigtailed acousto-optic frequency shifter (AOFS) with a large tuning range and tolerable transmission loss. In our recent experiment, we demonstrated that a doubly-resonant Fabry-Perot cavity can be used to enhance burst-mode UV laser pulses with arbitrary burst lengths and repetition rates [9].

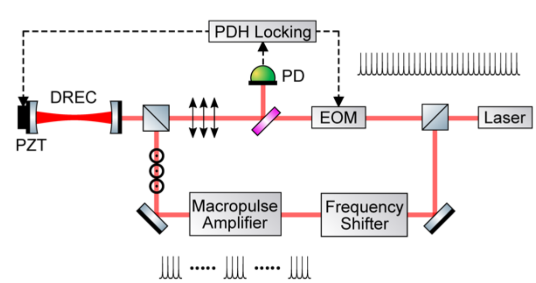

Figure 1: Locking principle of doubly-resonant enhancement cavity (DREC) operating with burst-mode laser pulses.

OPTICAL CAVITY

The high-power regime of enhancement cavities suffers from mirror surface degradation and laser induced damage of optical coatings. This effect is more serious in the shorter wavelength region as compared to the IR wavelength region where cavities are more tolerant to high power and tend to have higher damage thresholds. For our laser with

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50-ps/402.5-MHz, with the commercially available coating techniques at 355-nm, our experimental studies suggest that the power density must be below 100 MW/cm^2 to avoid laser induced damage. In order to realize 1 MW peak power inside the cavity, the spot size on the cavity mirror surface must be at least 2 mm or larger to avoid damage on the mirror coatings.

For this purpose, a Fabry-Perot cavity with large mode size has been investigated. Two features have been studied in the design to maximize the mode size: 1) the free spectral range of the cavity is set at half of the laser repetition rate and 2) the radius of curvature (ROC) of the cavity mirror is carefully chosen so that the cavity is operating near its stability edge. In the present setup, the cavity length is 744.8 mm and the ROC of the cavity mirror is around 372.5 mm with the corresponding stability factor g being -0.999. The resulting beam size on the mirror surface is about 2 mm in diameter. The cavity made of a stainless-steel structure to achieve a high structural stability and low thermal expansion. The entire cavity is enclosed in a vacuum chamber (up to 10^{-7} Torr) and equipped with vibration isolation materials from all directions. Alignment of cavity mirrors and coarse tuning of cavity length are conducted by using remote controlled pico-motor actuators. The experimental setup consists of a master oscillator, a burst-mode Nd:YAG amplifier with harmonic converters, a Fabry-Perot cavity and a feedback system as shown in Fig. 2. The master oscillator contains a fiber based seed laser and ytterbium-doped fiber amplifier (YDFA). The seed laser produces CW pulses of 80-ps at 402.5-MHz in 1064 nm. The output power from seed laser is pre-amplified by a polarization maintaining YDFA that provides an average output power of ~200 mW. 10% of the YDFA output is fiber-coupled to a second YDFA where it gets further amplified up to 10 W. The amplified IR beam is frequency tripled in the harmonic converter and injected into the doubly-resonant enhancement cavity (DREC) as a slave (auxiliary) beam. The remaining 90% is sent to the fiber coupled AOFS for frequency tuning purpose. The frequency tuned beam is further sent to a pulse picker system that selects 10 µs bursts at a low repetition rate (10 Hz) before being amplified in the flash lamp pumped Nd:YAG amplifier to produce high energy macropulses [10]. Finally, after passing through a series of harmonic converters, 50 ps, 402.5 MHz UV pulses at 355 nm with over 1 MW peak powers are produced. The burst-mode UV beam then is coupled into the DREC collinearly with the slave UV beam to establish double resonance.

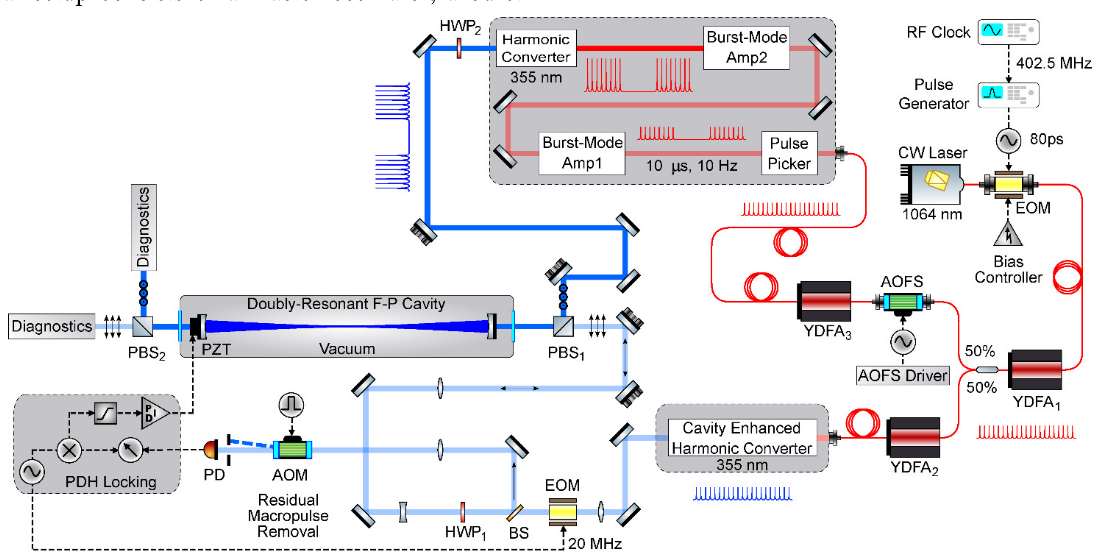

Figure 2: Experimental setup of burst-mode Fabry-Perot cavity for ultraviolet pulse enhancement in a double-resonance configuration. PBS, polarization beam splitter; QWP, quarter-wave plate; HWP, half-wave plate; PZT, piezoelectric transducer; PD, photodetector; EOM, electro-optic modulator; AOM, acousto-optic modulator; AOFS, acousto-optic frequency shifter; YDFA, ytterbium doped fiber amplifier; PDH, Pound-Drever-Hall.

EXPERIMENTAL RESULTS

The double resonance of burst-mode and slave UV beams is achieved by a two-channel fiber AOFS with a continuous frequency tuning range of 450 MHz (at UV) that well covers the free spectral range (FSR = 201.25 MHz) of the cavity. The AOFS is driven by an external Voltage Controlled Oscillator (VCO) which can be triggered to the laser macropulses and can take arbitrary waveforms to produce desired frequency shift in the burst-mode beam. The cavity is locked to the slave UV beam using the standard Pound-Drever-Hall (PDH) technique. When the cavity is locked, the frequency of the burst-mode UV beam is tuned with the AOFS to achieve its resonance to the cavity. Fig. 3. shows the waveform of the burst-mode UV beam transmitted from the cavity when the cavity is locked in a double resonance frequency setting with a constant frequency shift. At the double resonance condition, the peak power of the burst-mode UV pulses inside the cavity is estimated to be 1.05 MW for this case. At this power level, no laser-induced mirror coating damage has been observed.

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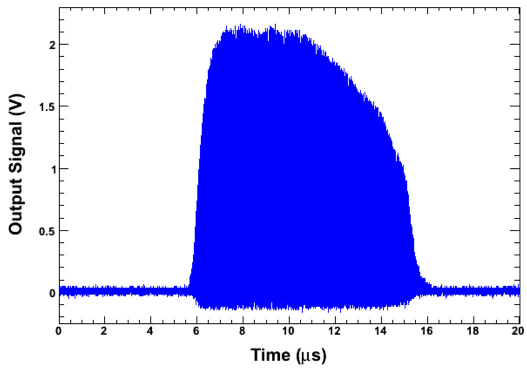

Figure 3: Typical macropulse waveform of the transmitted UV beam when the cavity is locked in a double resonance frequency setting with a constant frequency shift.

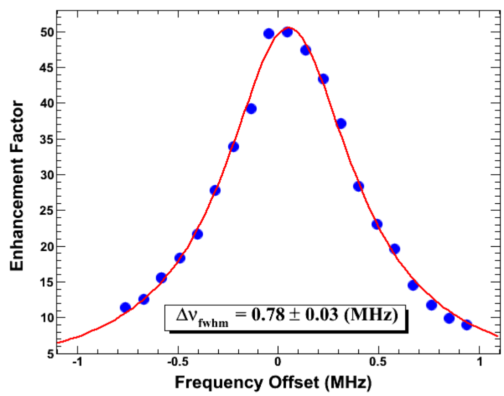

Figure 4: Frequency tuning curve of DREC at various frequencies applied to acousto-optic frequency shifter (AOFS). Dots are the experimental data, and red curve is the calculated results from the theoretical model.

Figure 4 shows the frequency tuning curve of DREC normalized to the enhancement factor of burst-mode UV beam while the cavity is locked to the slave UV beam. The frequency shift determines the resonance locking point where the burst-mode UV beam can be coupled the most to the cavity and therefore locked simultaneously with the slave UV beam. The red curve shows the theoretical fit to the experimental data. The full-width at half-maximum of the frequency tuning curve is ~0.78 MHz and the estimated cavity enhancement factor is close to 50 for this case. The cavity lock is quite stable to the vibration of chamber and ambient noise. This experiment demonstrated that the DREC can be used to enhance burst-mode picosecond UV pulses with MW peak power required for the laser stripping [2].

CONCLUSIONS

We have developed of large-mode Fabry-Perot cavity and established a locking of a burst-mode UV laser to the cavity. A power enhancement of burst-mode picosecond UV pulses with megawatt peak power has been demonstrated. We are planning to use this technique to achieve power enhancement of burst-mode picosecond UV laser pulses with 1-ms/60-Hz burst length required for the laser-assisted hydrogen ion beam stripping experiment at the Spallation Neutron Source.

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