Control of Amplified Spontaneous Emission in the Laser system for Intense Laser Plasma Acceleration Research

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Abstract. One of the emerging trends in new accelerator techniques is the laser based acceleration of particles, known as laser – plasma acceleration. Interaction of intense ultra short laser pulse with matter generates oscillations in hot plasma and the subsequent acceleration of electrons in a wakefield .Electrons can be accelerated to around 100 MeV within 1 mm distance. Ion beams can also be produced by laser plasma acceleration, though with a broader energy spectrum than achieved with electrons. Since laser- plasma acceleration offers the potential of compact accelerator technology, at BARC work has begun on the development of 20 terawatt pulsed laser system based on Nd:glass. Whether the laser plasma accelerator can produce high quality particle beams , depends on the characteristics of the laser pulse itself. These laser systems generally use the technique of chirped pulse amplification, where, after amplification the laser pulses are recompressed to obtain the high intensity required for laser plasma acceleration. The recompressed laser pulse temporal profile is very crucial for the best particle acceleration. The pulse should be free of a pedestal and pre-pulse, giving a high intensity contrast ratio (ratio of intensity of the short pulse to the intensity of the pedestal) for the recompressed pulse. The pedestal and pre pulse contains enough energy to create a plasma when the laser pulse is focused on target, before the arrival of the powerful femto-second range pulse. Amplified spontaneous emission (ASE) in the amplifier stages give the main contribution to the harmful pedestal. The optical scheme used in the front end amplifier stage that has been designed and developed to reduce the ASE is described. A detailed numerical analysis using Frantz & Nodvik rate equation model was done for the amplifier. We have found that by introducing an angular misalignment , inducing a differential loss for the main pulse to be amplified and the spontaneous emission, it is possible to increase the intensity contrast ratio by two orders of magnitude in the recompressed pulse. In the experimental set up too , for the amplification of the laser pulse, we have incorporated this method of misalignment to reduce amplified spontaneous emission . This should improve the temporal profile of the final compressed pulse.

1. Introduction

Acceleration of particles by intense laser plasma interactions is a fast evolving field, that opens up many new possibilities for next generation of compact accelerators. Ultra high intensity lasers can produce electric fields of the order of 100 GeV m^{-1}, surpassing those in conventional accelerators. Plasma particle accelerators are based on the principle that particles can be accelerated by the electric field generated within the plasma. High power lasers that fit into a not very large laboratory can now reach focused intensities of the order of 10^{19} W/cm^2. Such lasers are capable of producing beams of energetic electrons and protons. Many experiments have been done over the past few years, where high amplitude relativistic plasma waves, produced during laser plasma interactions have created electrons with energies of 100 MeV. Almost mono-energetic electron beams with 3% energy spread have been demonstrated[1,2]. The production of quasi – mono-energetic ion beams with an energy spread of 17% have also been shown [3] with intense laser plasma interactions. This technology has yet to be perfected. The biggest impediment to the wider use of this technology is the poor quality and reproducibility of the particle beam. In case of electron acceleration the energy of the bunch fluctuates . For a good accelerator the number of particles in the beam, their spread in angle, the spread in energy and the reproducibility matter. In order to achieve good acceleration the plasma as well as the laser pulses should be carefully controlled. The laser system being the principle tool in such an experiment has to be carefully designed. The three principle indicators of performance of such a laser system are the focused intensity, the pulse duration and the intensity contrast ratio.

Detailed knowledge of the temporal shape of the pulse is crucial. High density plasma physics experiments require a laser pulse with a high intensity contrast. A major concern is the unwanted energy preceding the actual pulse. A way of quantifying this unwanted energy is the intensity contrast ratio [4,5], which is the ratio of the peak pulse intensity to that of the pre pulse or background intensity. In case of Nd: glass laser a typical intensity contrast ratio will be 10^4 – 10^5 and therefore this background can contain significant energy. A pulse focused to 10^{18} W / cm^2 on target will see an intensity of 10^{13} W / cm^2 from the background itself. Therefore there will be a formation of an expanding pre plasma before the arrival of the main pulse. This will have a damaging effect on the quality of interaction and the physical phenomena being studied. So it is crucial to characterize and control the background accompanying the main pulse. For fast ion production a very good intensity contrast ratio is necessary because background intensity of 5X 10^9 W/cm^2 is enough to drastically affect the ion production. The recompressed pulse temporal shape is always accompanied with a pedestal or background. This temporal shape irregularity is due to spectral clippings and phase distortions in the chirped pulse amplification (CPA) scheme laser system and is of the order of picoseconds. These can be compensated for by the grating stretcher- compressor design and alignment techniques, so that the pedestal level is reduced. However , the regenerative amplifier that is an important part of the CPA system is responsible for a large part of the pedestal in the recompressed pulse. With the use of CPA technique in solid state lasers, shorter pulses, increased peak powers and therefore increased focused intensities have been obtained. In consequence as main pulse intensities are increased with improving system design, so must the intensity contrast ratio. The main source of pedestal is the amplified spontaneous emission (ASE) from the regenerative amplifier which cannot be removed easily from the CPA scheme and the ASE has a duration of several nanoseconds. A 150 fs pulse with an ASE background, and contrast ratio of 10^5 and typical duration of 5ns to 10 ns can contain as much energy as the main femto-second range pulse.

2.Numerical Analysis of Amplified Spontaneous Emission

In order to quantitatively estimate the effect of amplified spontaneous emission (ASE) on the amplification in a regenerative amplifier, and in order to find the parameters that largely effect the seed pulse amplification and the overall gain in a regenerative cavity, a detailed numerical calculation was carried out.

The regenerative amplifier design is essentially a multi-pass amplifier with a cavity geometry such that the injection of a chirped laser pulse and the ejection of the amplified pulse can be controlled by two optical switches. A seed pulse from an oscillator with a duration of about 150 fs is stretched to 800ps – 1 ns and is then introduced into the regenerative amplifier. The seed pulse (with an energy in the pico-Joule to nano-Joule range) circulates inside the cavity and extracts energy with each pass inside the cavity and is ejected out when the maximum energy is reached. As the seed pulse grows in amplitude, so does the amplified spontaneous emission of the active medium in the regenerative cavity. When no seed pulse is injected into the regenerative amplifier cavity, the ASE grows to a Q- switched pulse. We describe the “amplitude ratio” as the ratio of the peak amplitude of the short pulse (originating from the seed pulse) to the peak Q- switched pulse amplitude(originating from the cavity noise or ASE) in the regenerative cavity. This ratio will give an idea of , how much the ASE can be suppressed. A higher "amplitude ratio" would mean a diminishing Q- switched pulse underneath the circulating seed.

The amplification can be described with two coupled recurrence relations and these give the pulse fluence amplification and gain of each pass. Since the pulse widths under consideration here are much shorter than the lower level decay time (typically 10 ns-100ns , for solid state amplifying medium) two levels need to be taken into consideration- the upper laser level and the lower laser level. Pumping and other relaxation rates are insignificant. The two level nature of the amplifier allows one to use the standard rate equation model of Frantz and Nodvik [6] for pulse amplification. It describes the amplification process in terms of the pulse energy. If we assume that the amplifying medium can be characterized by a small signal gain coefficient, g_0 (cm^{-1}) and a length L (cm) and a saturation fluence E_s (J/cm^2) , then Frantz & Nodvik showed that for an input pulse energy fluence E_i , the output pulse energy fluence E_0 is given by

$$E_0 = E_s \ln\{1 + \exp(g_0 L)[\exp(\frac{E_i}{E_s}) - 1]\} \qquad (1)$$

The saturation fluence and the small signal gain are directly related to the population inversion in the two level system. This model by Frantz & Nodvik with the repeated application of the basic equations to a multi-pass system [7], adequately describes the regenerative amplifier . These equations have the same form as the equations that describe the photon density and population inversion in a Q- switched oscillator. Therefore the regenerative amplifier pulse train envelope has the familiar shape of a Q- switched pulse (figure1). We assume uniform transverse beam profiles and use the recurrence relation that relates the input energy fluence for pass number k, E_{in}^{k} to the output fluence E_{out}^{k} . The energy growth of the seed pulse as well as the growth of ASE to a Q- switched pulse is done simultaneously with E_{inq}^{k} and E_{ins}^{k} as the input fluence of the Q-switched pulse and that of the seed pulse respectively. Therefore E_{outq}^{k} and E_{outs}^{k} , the output energy fluence for the kth pass can be written as

$$E_{outq}^{k} = E_s \ln\{1 + \exp(g_k L)[\exp(\frac{E_{inq}^{k}}{E_s}) - 1]\}\ ;\ E_{outs}^{k} = E_s \ln\{1 + \exp(g_k L)[\exp(\frac{E_{ins}^{k}}{E_s}) - 1]\} \qquad (2)$$

$$E_{inq}^{k+1} = RE_{outq}^{k} \quad ; \quad E_{ins}^{k+1} = RE_{outs}^{k} \qquad (3)$$

For the (k+1)th pass the input energy fluence for the Q-switched pulse and the seed pulse is described by equation 3, which takes care of the reflection and scattering losses and R is that single pass loss. The small signal gain coefficient is modified in each pass due to the energy extracted from the stored energy of the inverted medium. The energy is extracted by the growing Q- switched pulse and the growing seed pulse as they circulate in the regenerative cavity. The initial spontaneous emission energy fluence in the cavity was estimated from the spontaneous emission contribution of all volume elements within a small solid angle ?? and a spectral interval ?? . The power of this noise can be written as [8]

$$P = hnK_{\Delta n} \frac{hnK_{\Delta n}}{s t} \frac{\Delta\Omega S_0}{4p} (G_0 - 1) \qquad (4)$$

Here h? is the energy of the photon and s is the stimulated emission cross section, $K_{??}$ is the part of the spontaneous emission matching the bandwidth of the amplifier and S_0 is the area of the beam. The initial spontaneous energy fluence in the regenerative cavity was estimated from the equation 4. This energy fluence will grow in the cavity into a Q-switched pulse , but it will be competing with the seed pulse for energy extraction from the gain medium of the cavity. With each pass the stored energy is depleted from the medium by the seed pulse as well as the growing

Q- switched pulse and therefore the small signal gain coefficient is modified. Therefore g for the (k+1)th pass can be written as the follows .

$$g_{k+1} = g_k - \frac{\Delta E_k}{LE_s} \qquad (5)$$

$$\Delta E_k = (E_{outq} + E_{outs}) - (E_{inq} + E_{ins}) \qquad (6)$$

From equation 1 it is evident that when the iteration for the regenerative amplifier is done, the peak energy reached by the injected seed pulse is independent of the initial seed pulse energy fluence. The maximum energy reached, remains constant , but the passes in the cavity required to reach the peak increases as initial seed energy decreases. This is the case when we do not consider the existence of amplified spontaneous emission (ASE) in the cavity. When ASE in the cavity is taken into consideration the amplified seed pulse shows variation in the peak extractable energy as well as a variation in the number of passes required to reach the peak and also the “amplitude ratio” changes with the seed pulse injection energy value. In figure 1 we show the output energy fluence as a function of pass number. To visualize the effect of initial pulse energy fluence variation on the “amplitude ratio”, we have calculated for four energy values of 500pJ/cm^2 , 700pJ/cm^2 , 1nJ/cm^2 and 2.5nJ/cm^2 .

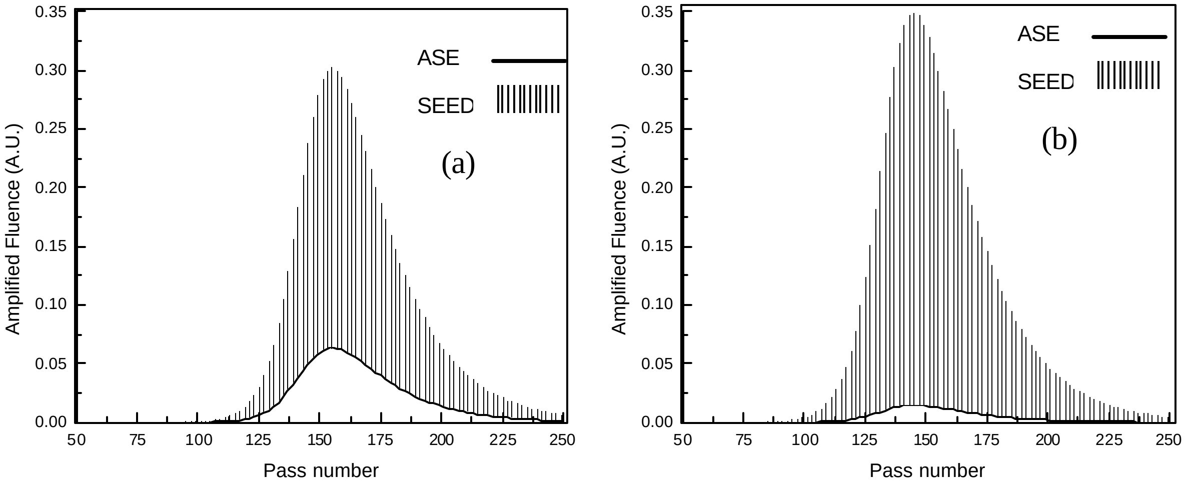

FIG.1. Seed pulse energy fluence vs pass number, illustrating the growth of the seed pulse and the ASE into the Q- switched pulse in the regenerative cavity for (a) 500pJ/cm^2 and (b) 2.5nJ/cm^2 . The columns represent the seed pulse as it amplifies in the medium overriding the growing Q-switched pulse.

As expected we find that with increasing seed pulse energy the Q-switched pulse diminishes . When the input fluence is 500pJ/cm^2 , the amplitude ratio is about 5:1 and with an input fluence of 1nJ/cm ^{2} , the ratio is 10:1. If the input seed pulse energy fluence is increased to 2.5nJ/cm^2 , the Q-switched pulse becomes insignificant with the amplitude ratio being 23:1. Figure 1. indicates how the growth of the ASE is restricted with increased seed pulse energy fluence. Experiments on the reduction of ASE by using cleaner and higher energy seed pulse injection into the regenerative amplifier have been done [9], and the results are encouraging.

Another method of restricting the growth of ASE is described below. In many experimental cases where a femtosecond range oscillator pulse, after its transit through a double pass stretcher has very little energy that can be injected into the regenerative cavity. Therefore when the input seed pulse energy is not too large and as a result the Q-switched pulse amplitude is significant, one could introduce a differential loss to the seed and the ASE as they grow in the cavity. We have taken the value for initial seed pulse energy fluence as 700pJ/cm^2 and worked out the amplification in the cavity , including this loss and found that the Q-switched pulse is almost non existent with an amplitude ratio greater than 23:1. Murray & Lowdermilk [10] had worked out the efficiency of coupling the pulse into the resonator cavity and found that it depends strongly on the alignment along the resonator axis. Here we have considered only the angular misalignment which is characterized by the angle a between beam axis and resonator axis , the distance ? between the beam waist and the point at which the axis cross [10]. We also assumed that there is no translational misalignment between the beam axis and resonator axis. The fractional coupling for misalignment is then given as

$$T = \exp\{-[(a\Delta / w_0)^2 + (a / f)^2]\} \tag{7}$$

where ?$_0$ is the waist radii and f = ?/p?$_0$. So the loss in each pass is included in the factor T, as

$$E_{inq}^{k+1} = TRE_{outq}^{k} \quad ; \quad E_{ins}^{k+1} = TRE_{outs}^{k} \tag{8}$$

Giving a slightly larger loss to the Q-switched pulse (or ASE) as compared to the seed pulse due to misalignment for the initial few passes, it is possible to achieve an amplitude ratio of 80:1 and an overall gain of 1.9X10^8 at a gain coefficient g_0 of 0.013cm^{-1} . Table 1 gives a comparative study of the "amplitude ratio" variation with the gain coefficient, the fraction of loss introduced and the number of passes that undergo the differential loss. In all the cases tabulated the seed pulse energy fluence is constant at 700pJ/cm^2 . Increasing the gain coefficient to 0.015cm^{-1} , the overall gain of the amplifier is 2.99X10^8 , retaining the same amplitude ratio. When the gain is increased to 0.02 cm^{-1} the overall gain is 6.2X10^8 and the amplitude ratio remains approximately near 80:1. Depending on the magnitude of angular misalignment, the number of passes that will undergo differential loss before the ASE and the seed pulse losses are equal is also calculated and tabulated in Table 1 for comparison. Thus we find that by introducing an angular misalignment induced differential loss, it is possible to pump in more energy into the gain medium and obtain a larger output ,while maintaining an amplitude ratio such that the Q-switched pulse is nearly absent.

A combination of a higher input energy of the seed pulse(before being injected into the regenerative cavity) and the introduction of differential loss due to angular mis-alignment can lead to a very large amplitude ratio and then to a very good intensity contrast ratio of the compressed pulse. For a seed pulse energy fluence of 700pJ / cm^2 , the amplitude ratio after amplification is about 6:1. If we assume that the amplified pulse is compressed to a 200fs pulse,and the background or pedestal of the pulse is about 5 ns, then the intensity contrast ratio works out to be about 10^4 . If the same seed pulse undergoes a differential loss in the regenerative cavity, with respect to the Q- switched pulse the amplitude ratio increases to 134:1 with an overall gain of 1.464x 10^8 (see Table 1). When this amplified pulse is compressed to a 200 fs pulse with a 5ns pedestal, the intensity contrast ratio is 10^6 . This is two orders of magnitude larger than the case when differential loss is not introduced in the cavity. With a higher seed pulse energy fluence of 2.5nJ/cm^2 , the amplitude ratio is 23:1 which is more than for the 700pJ/ cm^2 seed pulse case, as mentioned earlier. This will give an intensity contrast ratio of 10^5 . This higher energy seed pulse when injected into the regenerative cavity along with appropriate angular misalignment w. r. t. the Q-switched pulse, leads to an amplitude ratio of 180:1. Therefore a compressed pulse of 200fs with a pedestal of 5 ns would have an intensity contrast of 10^8 . This is three orders of magnitude larger.

TABLE I: COMPARISON OF AMPLITUDE RATIO ,TOTAL GAIN AND MIS ALIGNMENT LOSSES IN THE REGENERATIVE AMPLIFIER.

Small Signal Gain (g_0)in cm^{-1}	**Coupling Loss due to mis-alignment (T)**	**Passes with losses in ASE before ASE and seed losses are equal (K)**	**Amplitude Ratio: Max of Seed / Max of Q-switch**	**Overall Gain: (Max. of seed energy /700pJ/cm^2)**
g_0=0.01	0.06	20	22.8	3.744×10^7
		50	137.9	3.878×10^7
	0.05	20	18.6	6.01×10^7
		50	83.3	6.25×10^7
	0.03	20	12.38	1.22×10^8
		50	30.39	1.284×10^8
g_0=0.013	0.06	20	22.3	1.452×10^8
		50	134.8	1.464×10^8
	0.05	20	18.2	1.83×10^8
		50	81.3	1.912×10^8
	0.03	20	12.15	2.76×10^8
		50	29.7	2.89×10^8
g_0=0.015	0.06	20	22	2.41×10^8
		50	132.6	2.49×10^8
	0.05	20	17.9	2.88×10^8
		50	80.3	2.998×10^8
	0.03	20	11.9	3.94×10^8
		50	29.28	4.13×10^8
g_0=0.02	0.06	20	21.32	5.32×10^8
		50	127.6	5.52×10^8
	0.05	20	17.3	5.93×10^8
		50	77.2	6.20×10^8
	0.03	20	11.6	7.28×10^8
		50	28.2	7.609×10^8

3. Experimental setup

In our experimental set up we have incorporated this method of angular misalignment induced differential loss in the regenerative amplifier cavity. The regenerative amplifier cavity consists of two KDP Pockels cell, a quarter wave plate , a thin film polarizer and a Nd: silicate glass rod (10 mm diameter ,/ 150 mm long) placed between a curved mirror (6 m radius of curvature) and a plane mirror separated by 1.5m. It is during the seed pulse round trip time in the 1.5m cavity , that the ASE grows to be the 5ns – 10 nm problematic background pulse. The amplifier cavity is first optimized in the Q – switched operation after which the seed pulse is injected into the cavity. Then slowly the angular alignment of the end mirrors is disturbed with respect to the seed pulse injection alignment. The pulse amplification buildup can be detected from the leak pulse behind one of the end mirrors of the cavity. Figure 2 is the oscilloscope trace of the pulse growth in the regenerative cavity. It shows a well modulated structure with very very little Q- switched pulse background. This shows that the method of differential loss can be done experimentally.

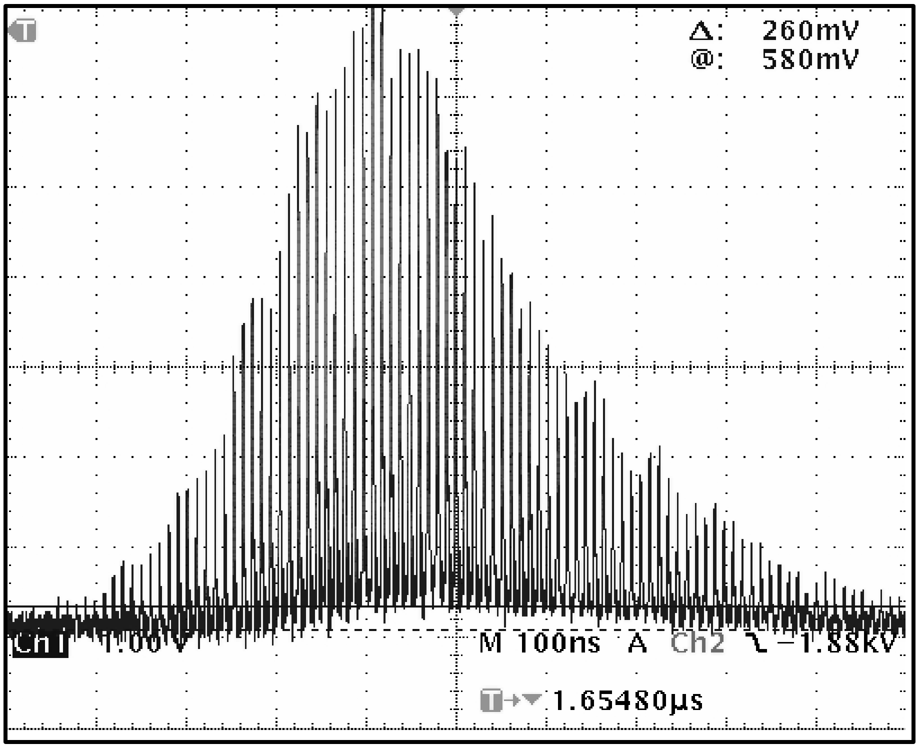

FIG2. Amplification of the circulating seed pulse detected from the leak of the end mirror. It shows the evolution of the seed pulse in the regenerative cavity when the alignment adjustments have been made for the elimination of the Q-switched pulse and reduction of ASE.

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