Proposed Beatwave Experiment at RAL with the Vulcan CPA Laser

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***Abstract*—A chirped pulse amplification (CPA) laser configuration capable of driving a plasma beat wave into saturation before modulation instabilities can grow is reported. The proposal is based on generating a single sub-ps, broad bandwidth pulse (∼16 nm) and stretching and filtering to select two wavelength components (separation ∼7 nm). The two spectral components are temporally stretched (to >100 ps) and separated (by ∼1 ns). The pulses are then amplified sequentially in a single Nd : glass chain to greater than 15 J per pulse. Using a single-pass reflective grating compressor, the pulses are compressed (from 2 to 5 ps) and automatically synchronized. The system is capable of introducing a chirp, such that the compressed pulses can compensate for relativistic detuning of the plasma wave. The optimum laser amplification and recombination configuration for generating a saturated laser-driven beatwave is presented, and options for future work are discussed.**

I. Introduction

Because the beatwave scheme was first proposed [1] as a possible electron accelerator, it has generated much interest [2]. The beatwave acceleration scheme is based on two laser beams of different frequencies resonantly driving a plasma wave at the difference frequency. Extremely large electric fields>GVcm^{-1} can be envisaged. Experiments have been conducted using microwaves [3], CO_2 lasers [4], [5], and glass lasers [6], [7] as the drive beams. In the experiments, the plasma wave was not driven to its limiting relativistic saturation level because of the growth of modulational instabilities, which have a growth rate determined by the ion plasma frequency. We here propose to generate chirped pulse amplified (CPA) laser pulses [8], [9] of sufficiently short duration and intensity to drive the plasma wave to saturation before modulation instabilities can grow. The proposed system generates two pulses, which are separated everywhere in time in the amplification system and temporally overlapped only in the interaction region. The system is inherently jitter free, which is an essential requirement to use short pulses. The system also avoids any nonlinear optical interaction between the pulses in the beam line, which can generate unwanted sidebands, complicating diagnostics.

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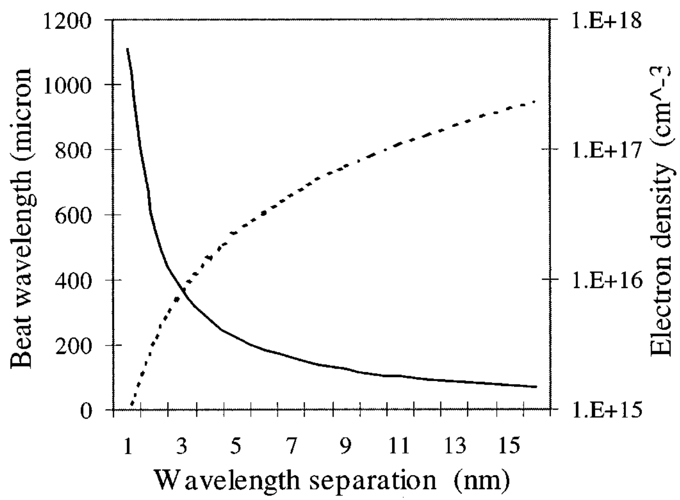

Fig. 1. Graph shows the beat wavelength (solid line) and the required electron density (dashed line) as a function of the wavelength separation of the two drive wavelengths centered on 1054 nm.

A requirement for a practical accelerator is that the radial gradients in the plasma wave should be smaller than the longitudinal field. To achieve this, a laser spot size comparable to or larger than the plasma wavelength λ_p is required. In Fig. 1, the plasma wavelength λ_p as a function of wavelength separation $\Delta\lambda = \lambda_0 - \lambda_1$ of the two laser components is plotted. This was calculated assuming that the beat frequency between the laser pulses is matched to the plasma frequency. The required electron density for resonant excitation of the plasma is also shown in Fig. 1. As λ_p is inversely proportional to $\Delta\lambda$, the required laser energy will scale as $\sim 1/\Delta\lambda^3$, favoring operation at the maximum possible drive laser wavelength separation. This is derived assuming a $1/\Delta\lambda^2$ energy dependence on focal spot size and an additional $1/\Delta\lambda$ dependence caused by the time required to reach saturation [10]. One-dimensional modeling [11] has shown that the modulational instability does not inhibit the plasma wave growth provided $I\lambda^2 > 10^{16}$ Wcm^{-2} μm^2. Thus, for $\Delta\lambda$ and pulse lengths of the order 10 nm and 5 ps, the required laser energy per pulse is of the order 10 J. This would give a relativistic saturated plasma wave amplitude $\delta n/n$ in the region of 10%.

Relativistic detuning of the plasma wave as it grows can be compensated by introducing a chirp [12] in the difference frequency between the two laser pulses as a function of time. This effectively changes the beat wavelength from the start to finish of the laser pulses to match the relativistic detuning in the plasma. Modeling has indicated that the effect of using a

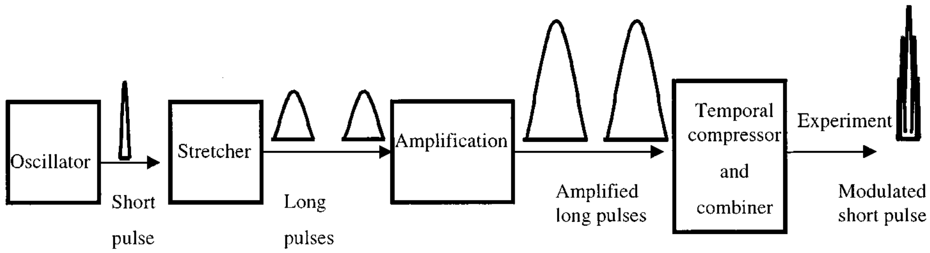

Fig. 2. Schematic diagram of the two-pulse CPA scheme.

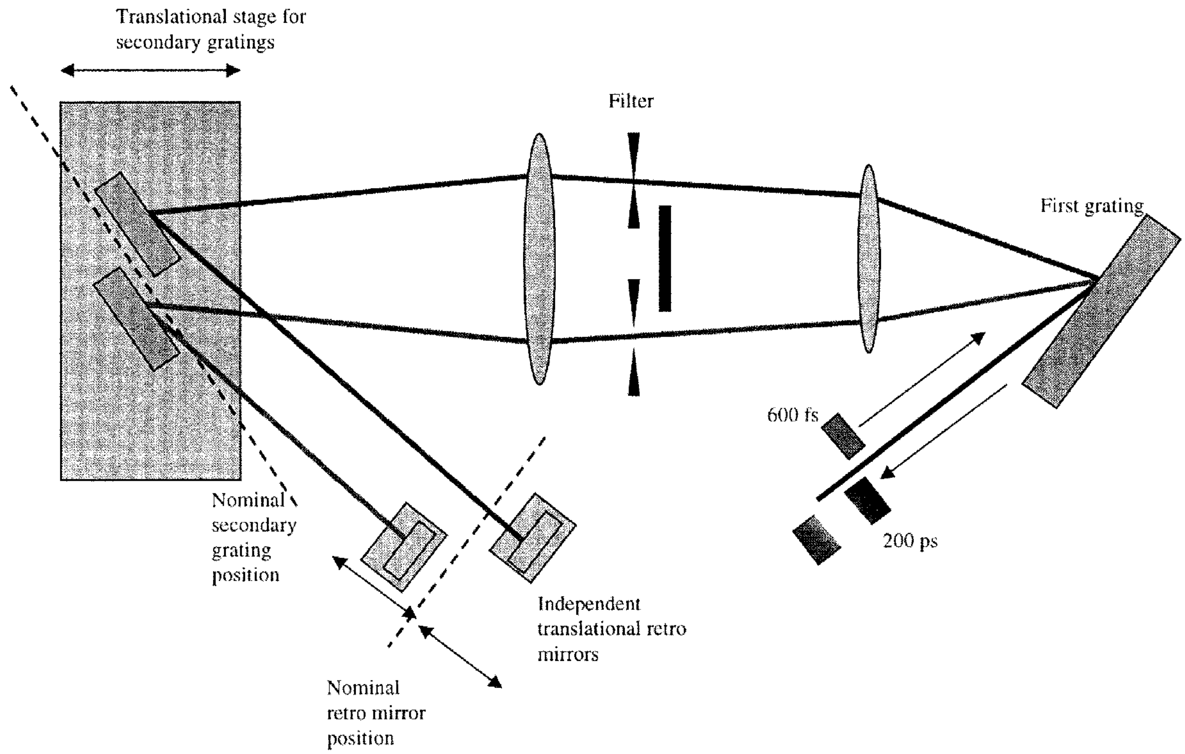

Fig. 3. Schematic diagram shows the stretcher. Independent motion of the secondary gratings and retro mirrors enables introduction of a controlled chirp of the beat frequency.

chirped difference frequency drive becomes more pronounced as the drive intensity is increased [13]. The CPA-based system we here propose is ideally suited for generating such a chirp.

There are considerable other advantages of using short laser pulses to drive the plasma wave, the most important of which is that a much larger density mismatch and inhomegenity can be tolerated, easing experimental requirements [14].

II. Laser Scheme

A layout of the Vulcan CPA system is shown schematically in Fig. 2. The initial oscillator pulse is generated by a commercial Kerr lens mode-locked oscillator using Ti : Sapphire as the active medium. It produces an 80-MHz pulse train of 5-nJ, 120-fs pulses of which one is used. The sech^2 pulse has a full-width at half maximum bandwidth of 16 nm centered at 1054 nm.

A. The Stretcher

The pulses are injected into a double-pass grating stretcher as shown in Fig. 3. An amplitude filter is used to select two narrow bandwidth portions of the input pulse. The bandwidth of each pulse is selected via the width of the slits, whereas the separation of the slits defines the wavelength difference and, hence, the beat frequency. The required amplitude filter is placed in the dispersed beam of the stretcher away from the Fourier plane. It is important to place the slits away from the Fourier plane because slits in this plane impose an extremely hard spectral clip on each pulse. Upon temporal compression, these hard clips would generate a pulse with a very poor temporal contrast after amplification, typically, no better than 100 : 1 many tens of pulse lengths away from the peak. By placing the slits away from this plane, the pulses are clipped in the near field and are thus selected with "softer" spectral edges and have better contrast ratios. This results in contrast ratio improvement of the amplified pulse of four to five orders of magnitude, as illustrated in Fig. 4.

An alternative scheme involving the use of an etalon placed inside an amplifier [15], which is regenerative, has been tested. However, this system is not as versatile as the stretcher described below, which can produce a changing beat frequency between the compressed pulses. This will be discussed below.

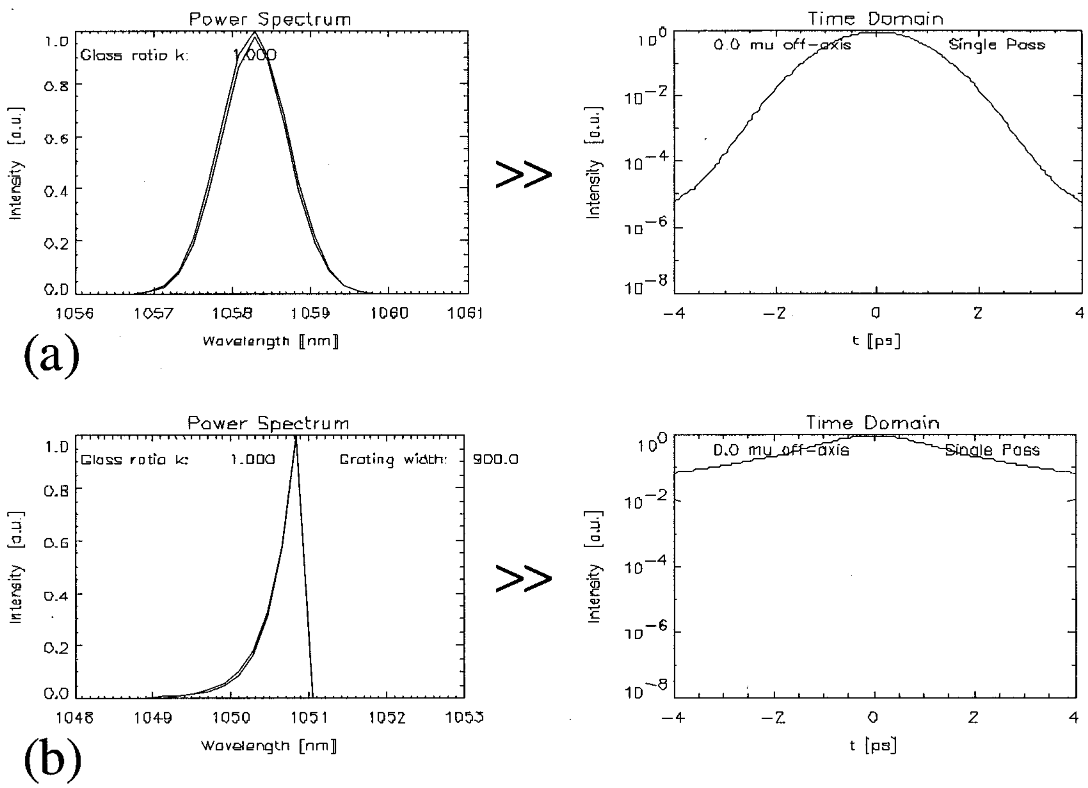

Fig. 4. Comparison of the power spectrum and pulse shape a soft- and hard-clipped pulse after amplification (a) filter away from the Fourier plane and (b) in the Fourier plane.

B. Introducing a Chirp on the Beat Frequency

A chirp in the wavelength difference between the compressed pulses beat can be realized in a straightforward manner, as indicated in Fig. 3. Two separate gratings, the locations of which are independently variable, replace the usual second grating in the stretcher. Also, two individual mirrors replace the retro mirror reflector, one for each grating. The two spectrally selected pulses can now be generated each with an arbitrary and different chirp. If the chirp parameter [16], $d\omega/dt$, for each pulse is β_1 and β_2, at the beat frequency $(\omega_2 - \omega_1)$, the frequency change after a time $\Delta\tau$ will be $\Delta\tau \cdot (\beta_1 - \beta_2)$. The chirp parameters β_1 and β_2 can be varied independently by changing the location of the gratings. For a few millimeter grating displacement, this frequency change can become comparable to the beat frequency.

The compressed pulse length of each pulse is determined by its bandwidth and chirp parameter. Thus, if two pulses are generated with different β's, they will have different pulse lengths if they possess the same bandwidth. This will limit the overlap time to the duration of the shorter pulse. Equal pulse lengths with different chirp parameters can be realized if each pulse has a bandwidth in proportion to its chirp. This is achieved by independently varying the slit widths and adjusting the grating positions to maintain the same pulse lengths. The intensity of the amplified compressed pulses can then be equalized by tuning the line center of the oscillator to effectively provide more energy for the narrower pulse.

For example, consider the case of two pulses centered at 1050 nm and 1056 nm, initially of equal bandwidth 1.0 nm. The unchirped bandwidth limited pulse duration will be $\sim$1.5 ps. Assuming that $\beta_1 = 4.5 \times 10^{22}$ Hz/s (6 ps/nm) and $\beta_2 = 9 \times 10^{22}$ Hz/s (3 ps/nm), the nominal beat frequency of 1.6×10^{12} Hz will be chirped at 4.5×10^{10} Hz/ps. The pulse durations will be approximately 6.2 ps and 3.4 ps. Thus, the beat will only occur over 50% of the temporal overlap and the chirp will change the beat frequency by about 10% over this overlap time of 3.4 ps. However, either by reducing the bandwidth of the 1050-nm pulse to 0.5 nm (case 1) or increasing the bandwidth of the 1056 pulse to 2.0 nm (case 2), 100% overlap can be achieved with the same rate of change in beat frequency with a pulse duration of either 3.4 ps (case 1, 10% change in beat frequency) or 6.2 ps (case 2, 20% change in beat frequency). In selecting the pulse bandwidth, a compromise must be reached between maximizing the laser energy and maintaining a low B-integral.

C. Amplification

The two pulses produced by the stretcher are temporally separated. We propose to amplify the pulses in a single beam line. The propagation and amplification of these pulses by the Vulcan Nd:glass laser has been be modeled numerically. In the simulation, a fluorescence curve for the phosphate glass amplifier, centered at 1053.5 nm, is used as the gain curve. A top hat function simulates the spectral filter of the stretcher.

The amplifier chain gain bandwidth significantly reduces the amplification available for the spectrally separated pulses the further they are located from the center wavelength. Fig. 5 shows the gain required as a function of wavelength to maintain a constant output of 20 J for a narrow bandwidth of 0.1 nm and a constant input energy from the oscillator of 1 nJ. However, such a narrow bandwidth cannot be amplified to the 20-J level through the Vulcan system. This is because if the bandwidth is too narrow, the stretched pulse length is short and the energy it can be amplified to is limited by damage thresholds and B-integral effects. Taking these factors into account, the wavelength separation as a function of bandwidth is presented in Fig. 6. This illustrates that larger separations necessarily need larger bandwidths. The gain available in the Vulcan amplifier chain is such that pulses at the 20-J level can be generated for $\Delta\lambda \sim 9$ nm with a bandwidth of $\sim$1.3 nm. The use of mixed phosphate and silicate glass amplifiers could in the future allow pulses of greater wavelength separation to be used in the system.

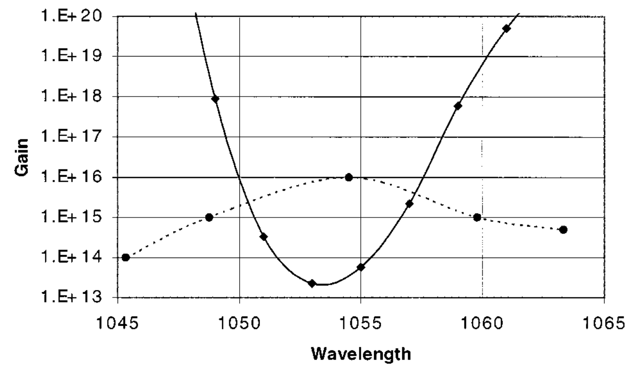

Fig. 5. Graph shows the required gain (solid line) in the Vulcan Nd : glass as a function of wavelength to maintain constant output energy of 20 J for 0.1-nm bandwidth pulse. The dashed line shows the system gain with an additional 9-mm diameter rod amplifier. The intersection represents the maximum wavelength difference the system can be used at.

III. Pulse Compression and Combining

A two-grating compressor is shown in Fig. 7. Both laser pulses are incident onto the first grating and overlap only partially on the second grating, as they diffract apart after leaving the first grating because of their different wavelengths. Thus, in the interaction region, not all of the initial energy in the pulses is used to drive the beat wave. D is the distance between the grating centers, L is the length of the gratings, p is the grooves density per meter, and N is the diffraction order at which we can define a cutoff wavelength $\lambda_{\rm cut}$. For a single beam illuminating the first grating composed of two monochromatic components equally spaced about a central wavelength by $\sim\lambda_{\rm cut}/2$, they will diffract out to such an extent that they both just miss the second grating and no energy is transmitted through the system. $\lambda_{\rm cut}$ is given by

$$\lambda_{\rm cut} \approx \frac{2L\cos^2\phi_{\rm out}}{NpD}. \quad (1)$$

Each wavelength component will fill a fraction $(1-\Delta\lambda/\lambda_{\rm cut})$ of the final grating resulting in an overlap fraction of $(1-2\Delta\lambda/\lambda_{\rm cut})$. If we require the beams to overlap significantly (i.e., at least overlap over the central half of the final grating), we can define a maximum wavelength separation $\Delta\lambda \le \lambda_{\rm cut}/4$. The present Vulcan compressor uses two 1740 lines per millimeter CPA gratings that have a surface ruling across 390×190 mm and are used in first order with a grating separation of 3.5 m and at an input angle of 73.2°. This gives $\lambda_{\rm cut} \sim 30$ nm. Therefore, to use the existing system would give a maximum wavelength separation of $\Delta\lambda \le 7$ nm. This corresponds to a plasma wave $\lambda_p \ge 158$ μm.

The three-grating compressor shown in Fig. 8 does not suffer from the problem of limited beam overlap. In this scheme, the two input pulses must be on different beam lines that are incident onto two separate input gratings. In this scheme, the beams must diffract sufficiently that when the two input gratings are just touching, full beam overlap is obtained on the final grating. This condition can be expressed as $\Delta\lambda = \lambda_{\rm cut}/2$. By appropriately increasing the separation between the input gratings, full overlap on the second grating can be achieved at $\Delta\lambda \ge \lambda_{\rm cut}/2$. An additional degree of freedom is available in that it is possible to move the input gratings in opposite directions relative to the output grating and introduce temporally dependent opposite chirps on the two pulses. It should be noted that the three-grating compressor requires amplification of the pulses in separate chains or a suitable method of separating the pulses before the input gratings.

The maximum intensity $I_{\rm max}$ in the focal region that can be delivered using a two-grating compressor for a beat wave experiment is given to a first-order approximation by

$$I_{\rm max} = SD_T e_d^2(1-\Delta\lambda/\lambda_{\rm cut})\left(\tau\pi\lambda_p^2\right)^{-1} \quad (2)$$

where S is the surface area of the gratings, e_d is the diffraction efficiency, and D_t is the damage threshold energy density of the gratings. Experience [9] with the 1740 lines per millimeter, 1053-nm optimized, gold overcoated holographic gratings (supplied by J. Yvon) in the Vulcan CPA system has shown that sustainable long-term (hundreds of shots) average drive fluence is approximately 130 mJcm^{-2} for no detectable surface degradation. The diffraction efficiencies of the two wavelengths are equal to within a few percent. Setting the gratings at an input angle of 73.2° gives a measured first-order diffraction efficiency e_d of 89%. For $\Delta\lambda = 7$ nm, this gives $I_{\rm max} \sim 7/\tau$ (ps) $\times$ 10^{16} Wcm^{-2} with a Rayleigh length $\sim$ centimeter. In adapting the Vulcan system to support two narrow spectral components, self-phase modulation effects limit the maximum deliverable energy per pulse, reducing the above to $I_{\rm max} \sim 3/\tau$ (ps) $\times 10^{16}$ Wcm^{-2}. This estimate is approximate because it does not account for the fact that the beam has different sizes in the horizontal and vertical planes caused by the beam aperture being noncircular.

The two-grating compressor is much simpler to set up and is ideal in situations in which the spectral separation is small. In situations in which it is necessary to have a long duration stretched pulse in the amplifier to avoid nonlinear effects, the three-grating compressor is advantageous.

The Vulcan CPA system is currently being upgraded [17] to the PW level, and when completed in 2002, the system will be capable of delivering pulses suitable for a beat-wave drive. The system will use 1480 lines per millimeter gratings separated by 13.5 m, which gives $\lambda_{\rm cut} \sim 31$ nm, very similar to the present configuration. However, with an increase in grating size to $\sim$0.9-m diameter, the system will be able to support energies

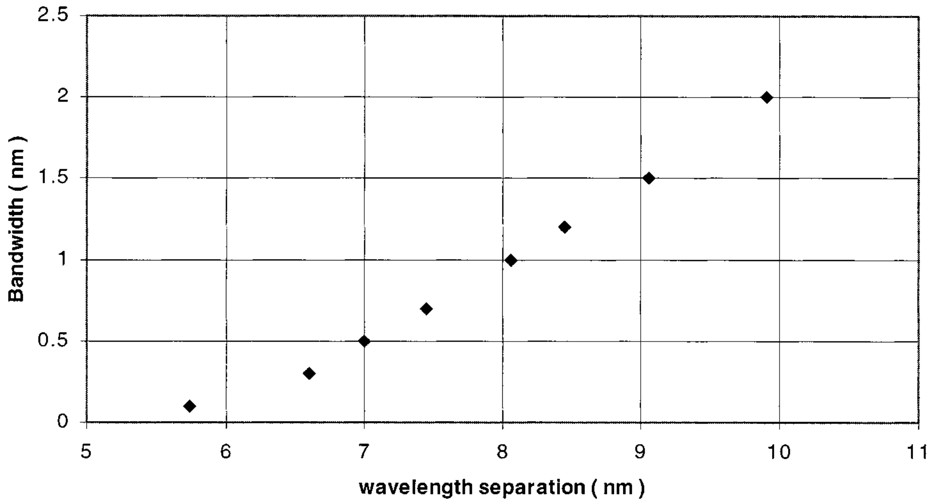

Fig. 6. Graph shows the minimum pulse bandwidth necessary to maintain ~ 20 J of energy per pulse as a function of the wavelength separation between the laser pulses on Vulcan. This limit is set to avoid damage thresholds in the amplifier chain and B-integral effects.

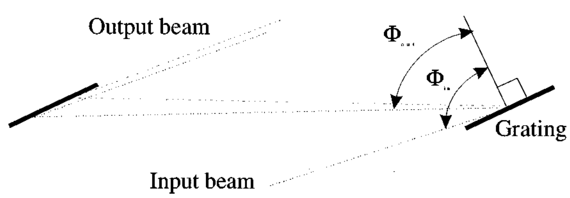

Fig. 7. Schematic layout shows a two-grating pulse compressor and combiner.

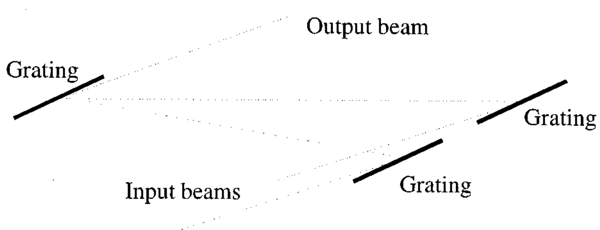

Fig. 8. Schematic layout shows a three-grating pulse compressor and combiner.

of $\sim$100 J per pulse, enabling much longer interaction lengths to be achieved.

IV. Summary

A novel laser configuration capable of generating the necessary conditions to drive a plasma beat wave into saturation before modulation instabilities can grow to cause significant disruption is proposed. The scheme relies on generating a single sub-ps, broad bandwidth pulse and spectrally stretching and filtering to select two wavelength components that are inherently synchronous. A stretcher capable of introducing a chirp such that the compressed pulses have a changing beat frequency capable of compensating for relativistic detuning is proposed. The two laser pulses can also be amplified on the Vulcan CPA Nd:glass chain greater than 20 J per pulse and will be used early in 2000 for a beat-wave experimental investigation.

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