UCRL-JC-152484

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September 9, 2003

3rd International Conference on Inertial Fusion Science and Applications, Monterey, California, September 7-12, 2003

TUPO1.26

ADVANCED COMPRESSOR DESIGNS FOR HIGH ENERGY PETAWATT PULSE GENERATION

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We discuss compressor designs for a proposedmulti-kilojoule, sub-picosecond beamline at the National Ignition Facility. A novel grating configuration reduces the size of the compressor chamber. Optimization of the design leads to a 4.7x1.4x0.4 m^3 minimum compressor volume.

I. INTRODUCTION

To convert a NIF beamline to achieve a Petawatt with high energy will require using chirped-pulse amplification[1], and the final grating in the compressor and any transport or focusing optics in the beamline after the compressor will be exposed to the full beam energy in an ultrashort pulse. This requires the development of large high-damage threshold gratings. Since the damage threshold can depend strongly on the incidence angle of the beam on the grating, it is desired that the final grating in the compressor operate at high incidence angles, typically >70°. In addition, the compressor design for the National Ignition Facility (NIF) high-energy petawatt (HEPW) system must fit within a footprint set by the physical configuration of the NIF building.

In this work, we discuss the development of compressor designs using such high-damage threshold gratings, which minimize the overall footprint.

II. CONVENTIONAL COMPRESSOR DESIGNS

Today, most of the compressors used in CPA laser chains use a 4-grating design[2]. In Figure 1, the first grating (G_1) creates a chromatic dispersion, which is cancelled by a second parallel grating (G_2). The output beam is collimated but with a spatial chirp on the beam (BC). These first two grating act as a compressor and induce a negative group delay dispersion that cancels the one induced in the stretcher. By tuning the grating separation, and incidence angle, one can compress the laser pulses to close to the Fourier limit. The difficulty, however, is that the residual spatial chirp can ruin focused beam. The addition of another pair of gratings (G_3 and G_4) in a configuration that is symmetric to the first pair compensates for the induced spatial chirp on the beam and eliminates this problem allowing a high pulse quality both in time and space.

For HEPW systems, the key parameters that we want to optimize in the compressor are the output energy and the compactness of the optical set-up. The size of such a compressor must fit into to the NIF target hall between the 12-foot thick radiation wall located 6 meters from the main target chamber.

Maximizing the output energy can be done at least two ways. First, the efficiency of the gratings must be maximized. Second, the compressor design should be such that the fluence onto the gratings is compatible with the grating damage threshold. Preliminary modeling studies suggest energy handling increases with the angle of incidence on the gratings, which also increases the illuminated area. Manufacturing constraints limit the size of gratings and it is currently believed that the practical limit is approximately two meters.

Minimizing the overall compressor size is strongly related to the grating separation. To decrease this separation, we need to increase the dispersion, which can be done by increasing the groove density for the gratings, and/or choosing appropriate incidence angles.

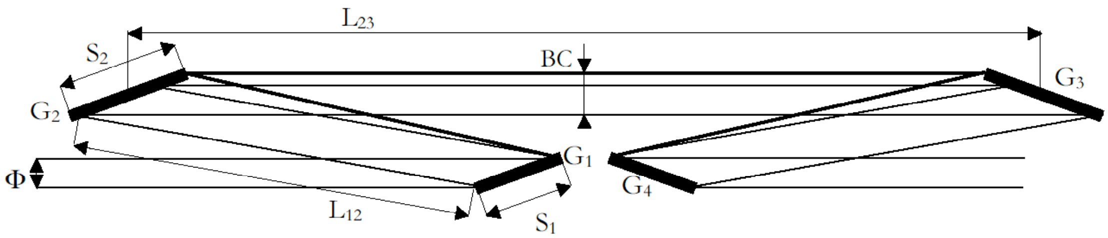

Figure 1 Conventional four-grating compressor.

We have studied 4-grating compressor designs for three groove densities: 1740 mm^{-1}, 1800 mm^{-1} and 1840 mm^{-1}. We have considered recompressing pulses initially stretched to 1.25 ns or 2.0 ns with either 0.8-nm or 4.0 nm bandwidths. These groove densities correspond to grating designs that our studies indicated as promising for achieving high damage thresholds. The 1.25-ns and 2-ns stretched pulse durations would yield B-limited energies of 6-kJ and 9-kJ, respectively, from the NIF chain. The bandwidths correspond to either 2-ps or 400-ps pulses final pulse widths.

We present below results for 1740 mm^{-1}. The results for 1800 mm^{-1} and 1840 mm^{-1} are similar to those for 1740 mm.

II.A. Compressor geometry and parameters

The geometric parameters of the compressor as shown on Figure 1 are:

Φ: the beam diameter.

S_1: the imprint on 1st grating.

S_2: the imprint on 2nd grating.

L_{12}: the propagation length between 1st and 2nd grating (for central wavelength).

BC: the beam diameter after 2nd grating in dispersed plane.

L_{23}: the minimum length between 2nd and 3rd grating (so that grating #1 and #4 do not overlap).

ϕ'' (fs^2.rad^{-1}) : the group delay dispersion.

All these parameters are determined when given the grating groove density, the angle of incidence θ_i, and the stretch factor, $\alpha = \Delta t/\Delta\lambda$. Here $\Delta\lambda$ is the spectral bandwidth and Δt is the pulse duration at the input of the compressor.

It is important to notice that this ratio is constant regardless of gain narrowing in the amplification chain.

An additional constraint is that the second grating does not clip the incident beam. For this to be true :

$$L_{12} \geq \frac{\Phi}{\sin(\theta_i - \theta_d)}\left(1 + \frac{S_2 - S_1}{2S_1}\right) \tag{1}$$

Note: the relationship between the FWHM and 1% pulse durations is (for a gaussian temporal shape):

$$\Delta t_{1\%} = \sqrt{2\ln 10/\ln 2}\,\Delta t_{FWHM} \tag{2}$$

II.B. Results

Δt	$\Delta\lambda$	qi	L_{12}	L_{23}	S_1	S_2 (1%)	BC (1%)	BC (FWHM)	GDD
ns	nm	deg.	m	m	cm	cm	cm	cm	fs^2.rad^{-1}
2	4	62	2.32	5.26	76	118	55.5	43.3	3.0 10^8
2	4	65	3.35	7.47	84	126	53.5	42.6	3.0 10^8
2	4	70	4.78	10.5	104	147	50.1	41.3	3.0 10^8
2	4	72	5.26	11.5	116	158	48.7	40.8	3.0 10^8
2	4	78	6.37	13.7	172	214	44.5	39.1	3.0 10^8
2	0.8	62	11.6	23.6	76	118	55.5	43.3	1.5 10^9
2	0.8	65	16.8	34.3	84	126	53.5	42.6	1.5 10^9
2	0.8	70	23.9	48.5	104	147	50.1	41.3	1.5 10^9
2	0.8	72	26.3	52.9	116	158	48.7	40.8	1.5 10^9
2	0.8	78	31.8	61.7	172	214	44.5	39.1	1.5 10^9
1.25	4	62	1.45	3.54	76	102	48	40.5	1.8 10^8
1.25	4	65	2.1	4.96	84	110	46.8	40	1.8 10^8
1.25	4	70	2.99	6.92	104	131	44.7	39.2	1.8 10^8
1.25	4	72	3.29	7.57	116	142	43.9	38.9	1.8 10^8
1.25	4	78	3.98	9.19	172	198	41.2	37.8	1.8 10^8
1.25	0.8	62	7.3	15	76	102	48	40.5	9.0 10^8
1.25	0.8	65	10.5	21.7	84	110	46.8	40	9.0 10^8
1.25	0.8	70	15	30.7	104	131	44.7	39.2	9.0 10^8
1.25	0.8	72	16.4	33.4	116	142	43.9	38.9	9.0 10^8
1.25	0.8	78	19.9	39.2	172	198	41.2	37.8	9.0 10^8

Table 1 Values of the parameters of the 4-grating compressor for different stretch factors (Δt/$\Delta\lambda$). The input beam is assumed to be a square super-Gaussian with linear dimensions of 35.8x35.8 cm^2 and total area of 1280 cm^2. Actual deployed gratings will require consideration of slightly larger beam area. The groove density is 1740 mm^{-1}. The shaded rows highlight geometric impossibilities.

In Table 1, we give the designs for 1740 mm[-1], for 4 different stretch factors $\eta = \Delta t / \Delta\lambda$. The shaded rows indicate geometric impossibilities.

The minimum size for such compressors is at least 10 meters for $\Delta\lambda$=4 nm, which is incompatible with the volume allowed for the compressor in the NIF building. The situation is much worse for narrow bandwidth pulses The minimum size of a 0.8-nm bandwidth pulse is at least 20 m.

III. ULTRACOMPACT COMPRESSOR DESIGNS

Since the compressor designs for limited bandwidth pulses are incompatible with the NIF target hall, a different geometry needs to be considered. It is desirable to produce a compressor in which the output beam is offset from the input beam by at least one beam diameter so that a mirror can be used to direct the beam to another focusing mirror. While increasing the grating separation in one the half of a conventional 4-grating compressor will generate such an offset, if we generate this offset by shortening or stretching a conventional, matched grating pair pulse compressor, the system would lose its symmetry and then produce a spatial chirp on the beam at the output of the compressor.

One solution to these requirements is the widely used 2-level compressor in which a 2-grating compressor is a double-passed using a roof mirror that changes the height of the beam. This cancels out the spatial chirp on the beam. An offset can be created if the design makes the lateral separation between the two gratings larger than a beam diameter. Because of the double-pass, this kind of compressor is at least twice smaller than a two-grating only compressor, while avoiding the spatial chirp on the beam; however, because of the need for multiple deployment of HEPW beamlines, it is desirable to have in plane compressor designs that may be stacked vertically.

There exists another compressor that eliminates spatial chirp and which requires about half the volume of the 2-level compressor because it is a one-level only as illustrated in Figure 2. This folded compressor consists of two half-compressors, with slightly different dispersion. Since the lower dispersion grating pair requires a larger separation to produce the same spatial chirp on the beam (and pulse delay) than a higher dispersion grating pair, the result is an offset in the output beam path relative to the input beam path. These two half-compressors are designed to have the same spatial chirp on the beam, so that no spatial chirp is present on the output beam.

In the following, we discuss the procedure to optimize the design of such a compressor and present optimized designs that could fit easily in the NIF target hall.

III.A. Optimization of Compact Compressor

To design this type of compressor, we assemble two half compressors together and eliminate any spatial chirp on the output beam by constraining the spatial chirp on the beam generated by each of the half compressors to be the same.

The key parameters for this optimization are :

- GD_1 and GD_2 : the groove densities for each half compressor.
- θ_{i1} and θ_{i2} : the incident angles.
- L_{12} and L_{34} : the path between the gratings.
- Offset : Offset between the outgoing and incoming beam optical axes.

This means we have three new parameters from the conventional design. The constraints imposed by our design are the following:

1) The spatial chirp on the beam must be the same the output of each half compressor :

$$\frac{GD_1 L_{12} \cos(\theta_{i1})}{\cos^2(\theta_{d1})} = \frac{GD_2 L_{34} \cos(\theta_{i2})}{\cos^2(\theta_{d2})} \quad (3)$$

here θ_{d1} and θ_{d2} are the diffracted angles.

2) The two path lengths must be set so that the beam is offset at the output of the compressor :

$$Offset = L_{34} \sin(\theta_{i2} - \theta_{d2}) - L_{12} \sin(\theta_{i1} - \theta_{d1}) \quad (4)$$

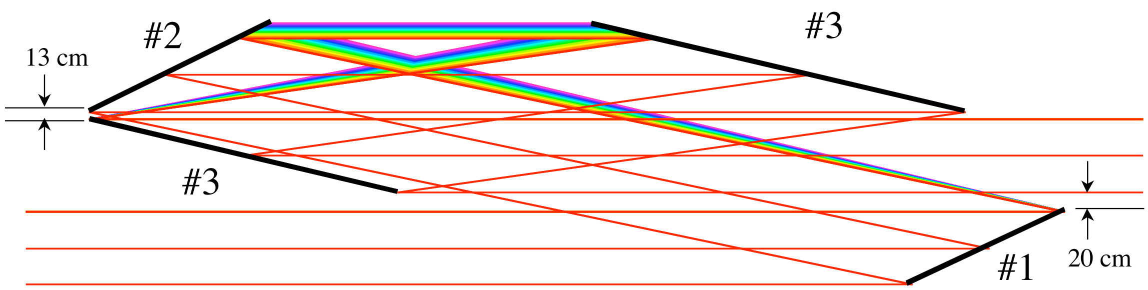

Figure 2 – Folded-compressor scheme using two half-compressors with matching spatial chirp.

3) The group delay is the sum of the group delay induced by each component, which leads to :

$$\tau = \frac{\lambda}{c}\left[\frac{GD_1^{\,2} L_{12}}{\cos^2(\theta_{d1})} + \frac{GD_2^{\,2} L_{34}}{\cos^2(\theta_{d2})}\right] \qquad (5)$$

In the conventional compressor design we have 2 degrees of freedom. We add three variables for two additional equations. This means we have now 3 degrees of freedom for the design of the compressor.

In most of the cases, we varied the groove densities and one of the angles of incidence. Since dispersion is higher when the groove density increases, the compressor size decreases when the groove density increases. However, if the dispersion is too high, the separation between the two gratings is small and the gratings clip the beam. Using 1800 mm^{-1} for the last grating we could always find a compact solution.

Our parameters were a beam diameter of 35.8 cm and a negative offset of 45.8 cm. This offset was chosen 10 cm larger than the beam size so that we could insert diagnostics or walls in between. The first grating groove density is set by the required stretched pulse duration. For 1.25 ns pulses, it should be less than 1700 mm^{-1} and for 2 ns, less than 1780 mm^{-1}.

Table 2 shows a compressor design for 1.25-ns stretched pulses with 4-nm of bandwidth.

III.B. Dispersion in a folded, offset, mixed-grating compressor

GD_1	1740 mm^{-1}	θ_{i1}	76.8°
GD_2	1780 mm^{-1}	θ_{i2}	76.7°
Width	5.5 m	Height	1.6 m
S_{max}	2.0 m	L_{23}	2.45 m
L_{12}	3.85 m	L_{34}	2.66 m
ΔT	1.25 ns	$\Delta\lambda_{FWHM}$	4 nm
Φ	40 cm	Offset	-60 cm

Table 2 Compressor design for optimized offset compressor

To understand the dispersion characteristics of this compressor design, we have designed a corresponding stretcher using only one groove density for all the gratings. Thus the compressor and stretcher will not match each other, and the spectral phase will not be completely compensated in the compressor.

There are two components to the spectral phase produced by this stretcher and compressor combination:

$$\phi_{mix}(\omega) = \frac{\omega}{c}\left(G_{12}\cos\theta_{d1} + G_{34}\cos\theta_{d2}\right) \qquad (6)$$

where G_{12} and G_{34} are the geometrical distances between gratings 1 and 2, and 3 and 4, respectively. The corresponding stretcher induces the spectral phase:

$$\phi_{str}(\omega) = \frac{\omega}{c}\left(G_{str}\cos\theta_{d,str}\right) \qquad (7)$$

where G_{str} is the distance between the gratings in the stretcher, and $\theta_{d,str}$ is the diffracted angle in the stretcher.

To minimize the overall dispersion of the system, we can adjust the three free parameters for the stretcher: the groove density, the grating separation and the angle of incidence. Since the bandwidth is low, matching the orders in a Taylor's series expansion of the spectral phase is possible rather than minimizing some metric of the pulse distortion caused by the residual phase. We ignore the zeroth and first orders since they only set the temporal origin and are irrelevant to the calculation. Since we have three parameters, we could compensate up to fourth order in spectral phase. Currently, we have only sought solutions that compensated to third order.

For the parameters in Table 2, we were able to make the second and third-order spectral phases vanish by tuning the angle of incidence and the grating separation while holding the groove density constant. For a stretcher with a groove density of 1780 mm^{-1}, we found a useful design at $\theta_{i,\,str}$ =81.9° and G_{str} = -1.41 m. This resulted in a predominantly quadratic residual spectral phase. We note that the design is only an initial test since the probable use of optical fibers to transport the signal and other media in the system that cause dispersion will need to be explicitly treated to obtain an accurate result.

IV. CONCLUSION

Using mixed-grating geometries allowed us to greatly reduce the size of the compressor required for a NIF Petawatt beam while eliminating the spatial chirp on the compressed beam. To our knowledge, this is the most compact design yet for a high-dispersion compressor. We expect to be able to design compressors between 5-m and 6-m long for multi-kilojoule pulse compression. In addition, this mixed grating compressor design has multiple degrees of freedom that may allow us to optimize the spectral phases of the output pulses.

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

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