

Broadband KrF laser, a possible scheme for IFE driver

I.B. Földes^{1,2} and S Szatmári^{1,3}

¹*HUN-REN Centre for Energy Research, Budapest, Hungary*

²*HUN-REN Wigner Research Centre, Budapest, Hungary*

³*Institute of Physics, University of Szeged, Szeged, Hungary*

Inertial confinement fusion (ICF) reached a breakthrough in 2022, when experiments on indirectly, x-ray driven fusion capsules resulted in fusion energy more than that of the laser system [1]. Since then, after further improvements on capsule smoothness and laser energy more than four times the laser energy was obtained from the fusion reactions. This was the consequence of α -particle heating which also proved that central ignition occurred. The positive output concerns to the laser energy only, and at present we are still far from producing total energy excess. Usable inertial fusion energy (IFE) requires however a gain of ~ 100 which cannot be reached with indirectly driven systems, due to the low (10%) coupling of x-rays to the DT capsule.

In order to overcome this problem direct drive systems are considered where the laser beams directly ablate the capsule wall. The visible radiation does not penetrate as deeply into the target as x-rays, therefore the ablation is less than for x-ray drive and the rocket effect of compression is less efficient, too. For efficient ablative acceleration short laser wavelength is preferred. Short wavelength and broad bandwidth are also preferred for reducing parametric instabilities which can be detrimental because of preheating, crossed-beam energy transfer (CBET) and energy losses. Most of the present efforts aim to use the second or third harmonics of diode-pumped solid-state lasers (DPSSL) [2]. A problem of DPSSL is that harmonic conversion is only efficient for narrow bandwidth. Especially this is a real problem for shock ignition [3] when a low intensity compression pulse is followed by a short spike producing a strong shock for ignition. According to recent considerations this is a serious limitation for realising energy production with IFE [4]. Excimer lasers are possible alternatives of DPSSL systems because they produce UV radiation without frequency conversion, namely either 248 nm wavelength in KrF or 193 nm in ArF. Although these systems require beam multiplexing [5], a total plug-in efficiency of $>7\%$ can be obtained in KrF and even higher is foreseen for ArF systems [6]. Alternative to beam multiplexing is pulse compression which was recently proposed for a two-sided target illumination with UV laser [7]. Although it is an interesting alternative, at present we do not have information about a realized or realizable laser efficiency. Excimer systems have been proposed either with conventional central spark ignition [8] or with fast ignition [9]. In the present paper we aim to consider the possibility for shock ignition.

Herewith we propose a new scheme with the seed pulse consisting of the output of several, oscillators detuned from each other. The discharge pumped KrF gain modules have typical

spectral width of about 0.4 nm in the emission of mainly amplified spontaneous (ASE) radiation. Due to the gain narrowing effect of stimulated emission even ASE radiation has noticeable gain narrowing. This becomes even more pronounced, as the number of amplification steps is increased in a resonator, leading to several times 0.1 nm bandwidth depending on the number of roundtrips. These properties were investigated in detail in the 90ies by Shaw et al. [10]. The homogeneously broadened transition of KrF has a flat-topped tuning curve of more than 1 nm bandwidth. In case when several detuned narrowband laser pulses are combined, the full gain width can be used for amplification which is broader than the small signal ASE spectrum.

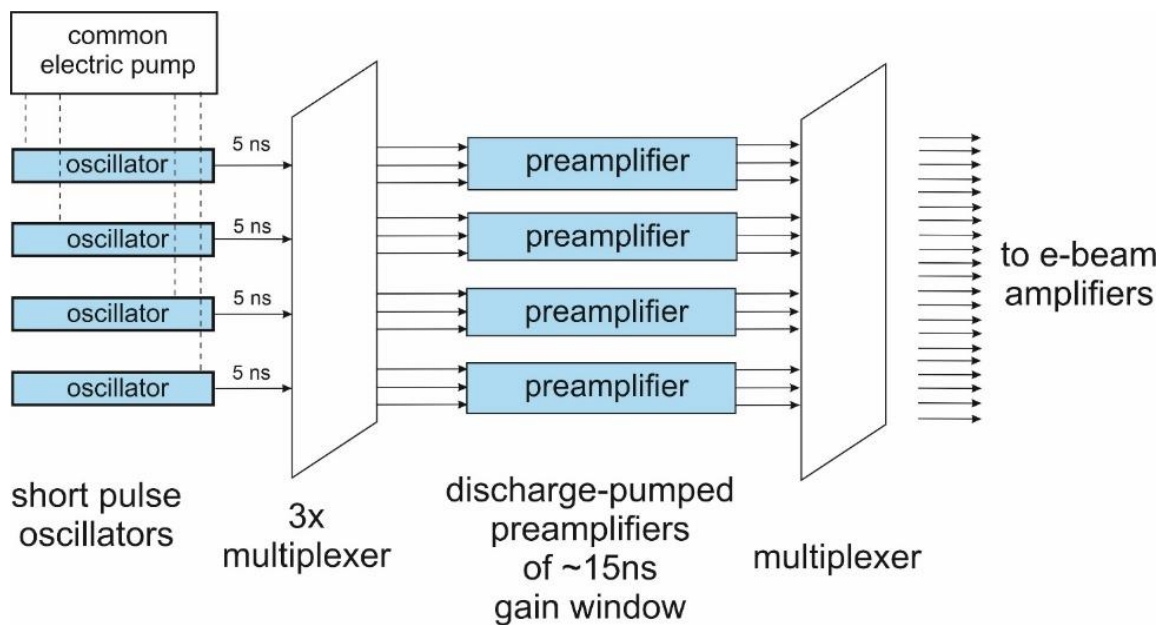


Figure 1: Multiple oscillators detuned from each other allow the use of the full gain bandwidth

Figure 1 shows a typical possible setup. In the picture four optically independent, spectrally selective oscillators detuned from each other provide narrow laser pulses of ~ 5 ns duration. The discharges are pumped by a common electric driver unit, therefore the pulses are well synchronized temporally. Discharge-pumped preamplifiers have a typical ~ 15 ns gain window, therefore the initial pulses are three times multiplexed to use the full pump duration. After the preamplifiers further multiplexing is carried out before amplification in the e-beam amplifiers. Similarly to the previous considerations [8] multiplexing is needed in order to use the whole duration of discharges, which corresponds to the longer gain window (>100 ns) of the e-beam amplifiers.

Calculations were carried out to find out the necessary number of separate oscillators. We combined oscillators of different spectral widths equidistantly shifted from each other. Figure 2 illustrates the results for oscillator bandwidths of 0.1, 0.12 and 0.14 nm. It is clearly seen that even in the case of the narrowest assumed bandwidth the radiation of 10 oscillators can efficiently fill the whole gain window. In the following amplifiers saturated amplification will smooth out the remaining modulations. In a recent paper[11] it was demonstrated that even in

the case when the seed pulses have maxima near the edge of the gain profile, the beam will be nearly flat-topped after amplification.

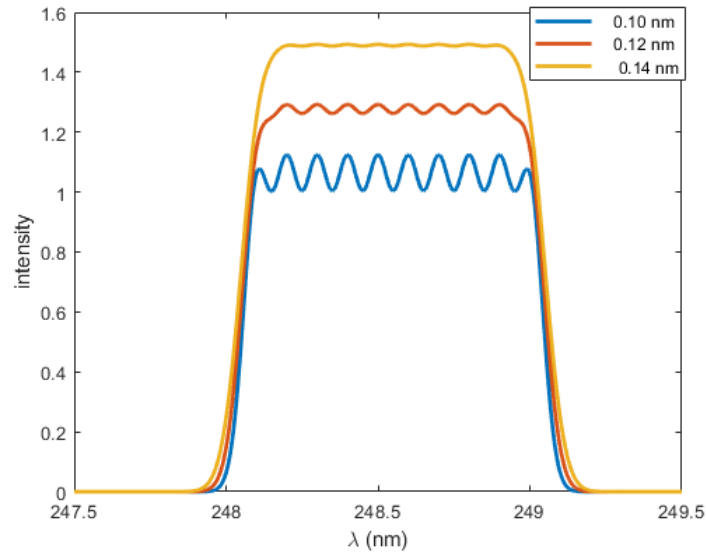


Figure 2: The sum of 10 detuned pulses of 0.1, 0.12 and 0.14 nm bandwidth fills the gain window of KrF. The total energy was not normalized in order to illustrate the modulation depth.

Thus, the suggestion based on the use of detuned incoherent oscillators is a reasonable alternative to the present approaches, where the spatial incoherence is obtained with induced spatial incoherence (ISI), requiring either an echelon grating or an imaging system [4]. The present proposal may give both spectral broadening and spatial incoherence. The obtainable ~ 3 THz bandwidth with spatially incoherent radiation allows the reduction of CBET for the spike causing the shock for ignition. Although according to recent estimations [12] stimulated Raman scattering may still be present, it is energetically a minor loss, moreover the accelerated electrons may contribute to the igniting shock.

Although these considerations were carried out for the KrF excimer, they can be well applied for ArF, too. ArF excimers are also homogeneously broadened, therefore the use of the full bandwidth is possible in a similar way. In that case the overall bandwidth can be as large as 10 THz, therefore the number of oscillators could change, depending on the available partial bandwidths. The number of oscillators seems to be large, but even if one takes separate discharges, the complexity is negligible in comparison with the following e-beam amplifiers, and with the long light paths of the multiplexed beams. Since typical wavelength-tuned excimer oscillators use only a small fraction of the discharge volume, even this complexity can be further reduced, if a single discharge is surrounded by several independent resonators which are spatially separated by a set of spatial filters as seen in Figure 3. Detuning of the resonators can be accomplished by an array of diffraction gratings stepwise slightly rotated with respect to each other. These resonators are then automatically synchronized. The use of multiple

oscillators detuned from each other could offer broad bandwidth and spatially incoherent UV radiation at the same time for inertial fusion in a simple manner.

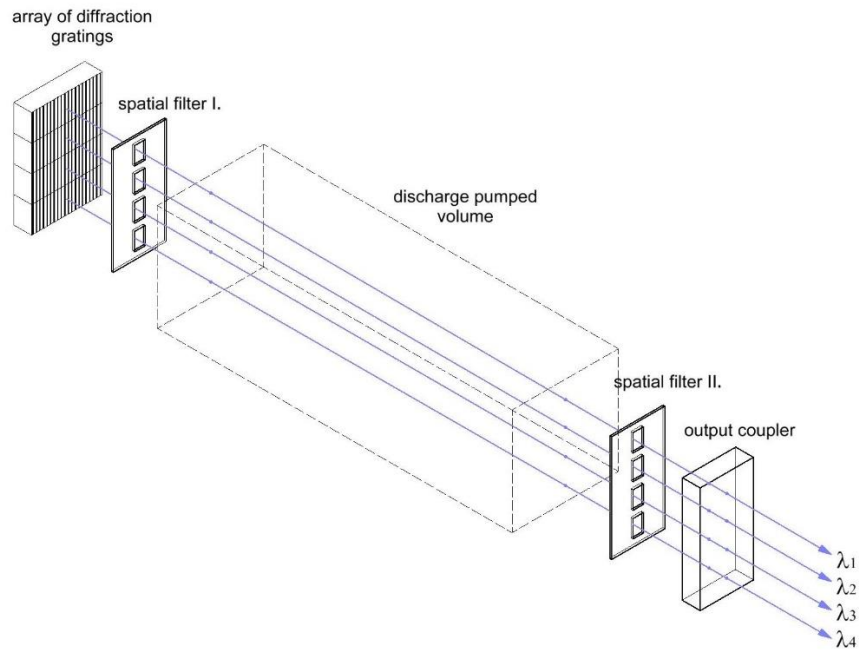


Figure 3: Possible arrangement of four detuned oscillators from a single discharge.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. The involved teams have operated within the framework of the Enabling Research Project CfP-FSD-AWP26-ENR-01 “Conceptual design for a European High Power Laser Fusion Research Facility”. The project also received funding from the National Research, Development, and Innovation Office (OTKA K138339 project) of Hungary.

References

- [1] A H. Abu-Shawareb, R. *et al*; Phys. Rev. Lett. **129**, 075001 (2022)
- [2] D. Batani et al., HPLSE, **e83**, 11(31) (2023)
- [3] R. Betti & C. Zhou; Phys. Plasmas **12** 110702 (2005)
- [4] S.E. Bodner; J. Fusion Energy **42**, 33 (2023)
- [5] S.P. Obenschain et al.; Phys. Plasmas **3**, 2098 (1996)
- [6] S.P. Obenschain et al.; Phyl. Trans. R. Soc. A **378**, 20200031 (2020)
- [7] C.A. Thomas et al.; Phys. Plasmas **31**, 112708 (2024)
- [8] M.W. Mc Geoch et al.; Fusion Technology **32**, 610 (1997)
- [9] I.B. Földes, S. Szatmári; Laser and Particle Beams **26**, 575 (2008)
- [10] M.J Shaw et. al., J. Chem. Phys. **105**, 1805 (1996)
- [11] M.W. McGeoch, S.P. Obenschain; Opt. Express **33**, 48423 (2025)
- [12] V. Tikhonchuk et al.; Phys. Plasmas **33**, 012107 (2026)