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MULTIPLE-BEAM FAST IGNITION WITH KrF LASER

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1. INTRODUCTION

The excellent beam quality and the short wavelength of KrF excimer lasers make them good candidates for IFE driver. Due to their short wavelength these lasers could also act as fast ignitors, since they can penetrate into the plasma of a significantly higher density, compared to infrared and visible lasers. If one wants to avoid the use of cones for fast ignitors (the application of which seems to be not feasible for a 5-10Hz regime of the planned IFE reactor), short wavelength and thus KrF radiation seems to be the real alternative. A recent proposal of Zvorykin et al. [1] suggests the use of the same KrF amplifier as a driver and as an ignitor as well.

It is easy to see that ~30 % increase of the pumping time of the e-beam pumped amplifiers of a planned IFE KrF test facility of 0.5 MJ laser energy[2] is satisfactory to obtain the required ignitor energy of ~50 kJ, whereas the driver pulse energy remains the same.

We suggest a novel multiple-beam fast ignitor scheme utilizing the special amplification properties of KrF lasers. It consists of hundreds of KrF pulses of ps duration, each focused separately onto the fusion pellet. Since the extractable energy from a KrF amplifier is independent of the pulse duration below ~100ps, the shortest practical pulse duration of ~1ps is targeted. The energy of the individual beams is chosen so that 1.8×10^{20} W/cm^2 focussed intensity for electron acceleration up to 1MeV can be obtained practically by single-beam amplification. This approach avoids beam demultiplexing which is the greatest difficulty associated with the usual single-beam (20ps) fast ignitor schemes.

2. PROPERTIES OF SHORT-PULSE KrF LASERS

A KrF fast ignitor scheme must rely on the special amplification properties of KrF amplifiers. The population inversion recovery time of the gain medium is τ_c~2ns [3], which is much longer than the duration of the ultrashort laser pulse, but shorter than the typical pumping time (60-300 ns) of the excimer amplifiers. It means that amplification of ultrashort pulses can be repeated in every 2ns, and one amplification step does not affect the subsequent amplification of pulses. The other important parameter of these short pulse KrF amplifiers is the maximum output energy density, which is ~5-6mJ/cm^2 for a pulse which is shorter than the ~2ns storage time of the KrF amplifier and short enough that repumping of the amplifier can be neglected. Thus in the case of short laser pulses the extractable energy density becomes roughly independent of the pulse duration.

The KrF amplifying medium has a bandwidth corresponding to a transform limited pulse of 100fs duration. Fast ignitors normally considered to use pulses of 20ps duration. On the other hand a transform limited pulse of the considered 20ps duration has a significantly narrower bandwidth than that of the KrF amplifying medium, thus correspondingly a much larger degree of temporal coherence. The coherence, however, may lead to destructive interference in beam demultiplexing. For this reason one should consider either 20 ps non-transform limited pulses of moderate temporal coherence, or beam smoothing techniques have to be applied, similarly to that used for long pulses, when unifying the beamlets with angular multiplexing, as suggested earlier[1]. Considering that the different beam-passes undergo practically independent optical distortions; both the direction and the focussability of the partial beams will be different, therefore the temporal and directional matching of the partial beams to a single ~20μm focal spot are critical. Therefore we consider fast ignitors using shorter, ~1ps beam. Note that it is the appearance of nonlinearities (self-focusing, multiphoton absorption, GVD effects during pulse propagation) which cause a practical lower limit of pulse duration to 0.5-1ps.

3. REQUIREMENTS FOR A FAST IGNITOR

Herewith we consider fast ignition using fast electrons. Numerical simulations[4] show that a nearly uniform density of 300-500g/cm^3 is optimal by the time of the ignition. Clearly, the present scaling laws[4,5] for the velocity and then for the range of the accelerated electrons suggest a laser energy of 30-100kJ for the fast ignitor. A problem of fast ignitors with longer wavelength is that the electrons will be too energetic for these intensities, therefore they will not be stopped efficiently. In case of using KrF lasers the near optimal electron energy of 1MeV can be obtained with 1.8×10^{20}W/cm^2 intensity.

We can estimate the requirements based on the recently suggested [2] fusion test facility. The 0.5MJ laser energy is obtained by using 20 moduls of $1m^2$ aperture, each providing 25kJ energy in a pulse of 2.5ns duration. Each amplifier is pumped by a 225ns long electron beam. Thus in a single pass of short pulse amplification this system is able to provide 1.2 kJ short-pulse energy with the $6mJ/cm^2$ extraction energy density. Its consequence is that for a 48kJ fast ignitor system 40 passes will be necessary covering 80ns pumping time. This will need the increase of the pumping duration of the e-beam from 225ns to 300ns which will require correspondingly more pumped-in energy for the total system.

In case of unifying energy of several ultrashort pulses with maintaining the directional properties of the partial beams the so-called interferometric multiplexing scheme[6] can be applied. The Sagnac interferometer - as discussed therein - combines generally two beams which follow the same optical path in the opposite direction, thus providing perfect wavefront matching. The scheme however cannot be applied for multiple beams. From a single amplifier of $1m^2$ diameter with the achievable 1.7 times increase of energy by 2-beam multiplexing, one can obtain 100J energy for a single beam after a 2-pass polarization multiplexing. This beam can be focused using an F/32 focusing optics – assuming a diffraction limited beam – to a focal diameter of 8 μm corresponding to the intensity of $2 \times 10^{20} W/cm^2$, which is sufficient for electron acceleration to more than 1MeV energy.

4. THE MULTIPLE BEAM FAST IGNITOR

Keeping in mind the above-mentioned energy constraints now we can get 400 beams, each with 100J energy. Note that in case the 2-beam interferometric multiplexing will provide 1.7 times increase of the single beam energy[6] the total energy of the scheme will be 40kJ instead of the previously given 48kJ which assumed additive amplifications. As each beam is able to provide the necessary intensity for the acceleration of electrons up to the required 1MeV energy, it is not necessary to synchronize the beams with 1ps accuracy. Furthermore the so-called coronal ignition model[7] claims that the fast ignitor is not sensitive to the location of the ignition in the corona. It opens the possibility that several pulses of 1ps duration are to be focused on different parts of the fusion capsule instead of the single ignitor pulse of 20ps duration. In this case the fast electrons will ignite the plasma possibly at different parts of the pellet, but the total energy balance remains the same. This scheme does not require directional matching of the beams, and it maintains the required accuracy of temporal synchronization of the pulses at ~20ps, even when using shorter (ps or subpicosecond) pulses. There might be a real problem, if the ρR product for each ignitor does not reach the required $0.1\text{-}0.3 gcm^{-3}$, although we think that in the isochoric case when the material density is high, it is not so serious. Clearly, electron-transport as well as ignition must be followed in 3D simulations for obtaining answer. However the separate pulses may be also focused to a single spot separately, in which case neither the temporal nor the full spatial synchronization is critical, it is sufficient to have a temporal synchronization to 20ps (without wavefront matching) and a spatial overlap within ~90μm because the beams can do their job separately.

The required 8μm focal spot corresponds to an F/32 focusing in the case of a diffraction limited beam. Then the greatest difficulty will be to fit all these focusing systems together with the main beam focusing within the 4π angle. In this case the focusing requires nearly 10% of the total solid angle. This can be reduced by the multiple use of the same focusing optics for several beams. Another possibility is to use self-focusing. Relativistic self-focusing of TW laser beams [8] may contribute to the compression of laser energy to a smaller spot if the intensity is above $10^{19} W/cm^2$ and it was even used in KrF laser experiments[8]. In the case when it contributes to the generation of smaller focal spots, the focusing conditions will be less stringent. It must be noted that even if the size of the laser spot is small, the electrons will diverge significantly until they reach the dense matter to be ignited. Detailed 3D simulations and experimental efforts toward interferometric multiplexing of large size beams is necessary to determine whether this scheme is feasible.

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