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Abstract: The plasma density profile plays a key role in the generation of 13.5 nm light for an extreme ultraviolet lithography (EUVL) source from laser-produced (LP) Sn-based plasmas due to the importance of opacity. We propose to characterize and optimize the plasma density profile to enhance conversion efficiency and mitigate debris using a double laser pulses technique. The basic idea is to separate generation and heating processes of the EUV plasma. Cold plasma is first generated by a low energy pre-pulse and then a main pulse heats the plasma to temperatures favorable for emitting efficient 13.5 nm EUV light. In this way, the plasma density profile can be controlled by verifying pre-pulse energy and the interval between pre- and main pulses. Higher conversion efficiency compared with solid density Sn should be expected due to the lower opacity. The minimum number of atoms required to generate efficient EUV light can be obtained using a low energy pre-pulse. And most of the atoms will be ionized; ions are much easier to be stop by applying electric and magnetic fields. In that way, a clean target supply method can be expected. Comprehensive parameters of plasma (density profile), EUV light (conversion efficiency, spectrum, angular distribution), and debris (production, energy spectrum, angular distribution) will be measured in detail. The physics dominating the role of plasma density profile on the properties of EUV light and debris will be investigated by comparing experimental data with the results of radiation hydrodynamic simulations.

1. Background

Moore's law, which states that the number of transistors on a chip doubles about every two years, has been kept effective for 40 years [1]. The current lithography technology, i.e. deep ultraviolet lithography, used to make microprocessors will begin to reach its physical limit in the coming years. Extreme ultraviolet lithography (EUVL) will hopefully provide next generation lithography tools in the semiconductor industry to continue Moore's law [2]. Engineering Test Stand (ETS) of EUVL has demonstrated its feasibility to produce several 10 nm structures in silicon wafer [3]. However, several challenges must be addressed before applying EUVL to mass production. One of those is to develop powerful, efficient, clean, high repetition rate EUV light sources. The requirements for an EUVL source from the semiconductor makers are that the power is larger than 115W at intermediate focus to achieve 120 wafers per hour throughout, and the lifetime is over 30,000 hours at 10 kHz or 10^{11} shots etc [4].

Because of heavy absorption of EUV light in air and most of the other materials, all of the optics in an EUVL system are reflective mirrors. At present, the only available optics with high reflectivity at normal incidence is multilayer Mo/Si mirror, which has a 2% bandwidth centered at 13.5 nm. So most of the efforts focus on monochromatic 13.5 nm EUV light. Two candidate sources are most hopeful to date: laser-produced plasmas and discharge-pumped plasmas [5][6]. Because of the potentially high conversion, controllable debris, and large collection ability, increasing efforts have been developed to laser-produced plasmas. Among the various target materials, Sn-based plasmas have shown the highest conversion efficiency (CE), 3% in 2% BW in 2π [7]. However, there is still a long way to go for Sn-based plasma 13.5 nm EUVL source. The conversion efficiency is much lower than theory predictions ~5% [8], until now there hasn't been a way to mitigate the heavy debris completely, and the problems related with high repetition rate operation are still unclear. In order to enhance CE and mitigate debris, there is a great need to understand the physics dominating the generation and transport of 13.5 nm EUV light in LP Sn plasmas.

The plasma density profile plays a key role in generation and transport of 13.5 nm EUV light from LP Sn-based on plasmas, because Sn plasma is optically thick to 13.5 nm light. The previous works have pointed out that most of 13.5 nm EUV light comes from the low density corona of laser-produced Sn plasmas due to its lower opacity [9][10]. Re-absorption induced by plasmas, both in EUV emission dominated and large scale low density corona, plays a key role in extracting 13.5 nm EUV light from Sn-based plasmas. Low density Sn doped foam targets containing much less concentration of Sn ions have shown comparable CE with solid density Sn [11] [12]. However, there are very few experimental data on plasma parameters of Sn-doped foam targets. It is possible to optimize plasma density to achieve higher CE.

Another critical issue for Sn-based targets is heavy debris generated from plasma. Low density Sn-doped foam targets and Sn-doped droplet targets reduce debris from Sn significantly because of their low concentration of Sn, however the EUV light is accompanied by a large amount of additional carbon and oxygen ions with very fast velocity. Although ambient gas, electric and magnetic fields can mitigate light ions efficiently, the requirements of EUVL systems are difficult to obtain. And it has been shown that the yield of ions from laser-produced Sn-based plasmas linearly depends on pumping laser energy [13]. If a low energy pulse is employed to generate plasma, debris will be mitigated significantly.

We propose to characterize and optimize the density profile of laser-produced Sn-based plasmas adopting double pulse technology. The purpose is to understand the physics dominating the processes of generation and transport of 13.5 nm EUV light and to enhance conversion efficiency and mitigate debris. The double-pulse technique has been widely used in laser-produced plasmas to enhance x-ray production for a long time [14], also has been applied to EUVL sources by several groups [15][16][17]. However, most of the efforts focused on characterization of EUV lights, there are few data on plasma parameters and properties of debris. We will perform detailed experiments and numerical simulations to clarify the effect of energy, pulse duration, interval of pre- and main pulses on CE and debris, various targets including solid density bulk Sn, thin foil Sn, thin coating Sn, low density Sn-doped foam will be investigated.

The role of plasma density profile on 13.5 nm EUV light generation and transport and the principle of the proposal to reduce opacity will be discussed in section 2. The experimental arrangement and diagnostics employed are presented in section 3. Initial simulation results about double pulse heating and future simulation works are given in section 4.

2. Principle of proposal

When a target surface is irradiated by the leading edge of a laser pulse, plasma is formed near the surface and expands into vacuum due to pressure gradient. The laser pulse interacts with the plasma, laser

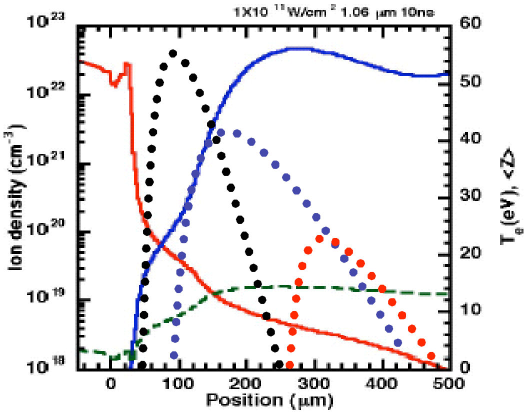


Fig. 1 Typical ion density, temperature, and ionization state (hydrodynamic simulation results)

energy is transferred into the plasma by various absorption mechanisms [12]. At the intensities favorable for efficient 13.5 nm EUV light (~1×10^{11} W/cm^2), the dominant mechanism is inverse Bremsstrahlung. Typical ion density, temperature, and ionization charge state of laser-produced Sn plasmas from radiation hydrodynamic simulation are shown in Fig.1.

Emission of laser-produced Sn-based plasmas is a semi-continuum peaking at 13.5 nm. EUV emission near 13.5 nm can be attributed to 4d-4f, 4p-4d, and 4d-5p unresolved transition array (UTA) of Sn ions with ionization charge state from 8+ to 13+ [18] . The properties of 13.5 nm EUV light strongly depend on plasma parameters. Populations of ions with various ionization charge state are determined by the temperature of the plasma. Favorable temperatures for emitting 13.5 nm light are from 30 to 60 eV. A flat temperature profile will be helpful to reduce the satellite lines from ions with lower or higher charge states, and then to achieve a narrow band emission.

Because dense Sn plasma is optically thick to 13.5 nm light, its output depends on not only the emissivity but also opacity of the dominant EUV emitting region and long scale corona. If the dominant emitting region located at dense region, although emissivity is high due to the high ion density, most of the EUV light can't escape from the plasma due to re-absorption. There should be an optimal condition in which the emission dominant region is so located that the corresponding emissivity is high enough to generate efficient EUV light but the opacity is low enough to extract EUV light efficiently from the plasma.

Experiments and hydrodynamic simulations have shown that the most efficient EUV emission is generated at laser intensities from 5×10^{10} to 1×10^{11} W/cm^2. In those cases Te in the corona is from 30 to 60 eV, which is very close to those the favorable temperature for 13.5 nm EUV emission. Then most of the EUV emission comes from the coronal region. At higher intensity, the temperature in the corona region is too high; therefore, most of the EUV emission comes from the high density region. Sn plasma in the high density region has very high opacity. Furthermore, EUV light is absorbed by the long scale out-layer plasma, so that EUV light emitted the from dense plasma can not efficiently escape. Less opacity effect and suitable emissivity in well under-dense plasma region results in higher conversion efficiency. Previous investigation on the plasma density profile of solid Sn plasmas has shown that the dominant emission region is located in the well under dense region.

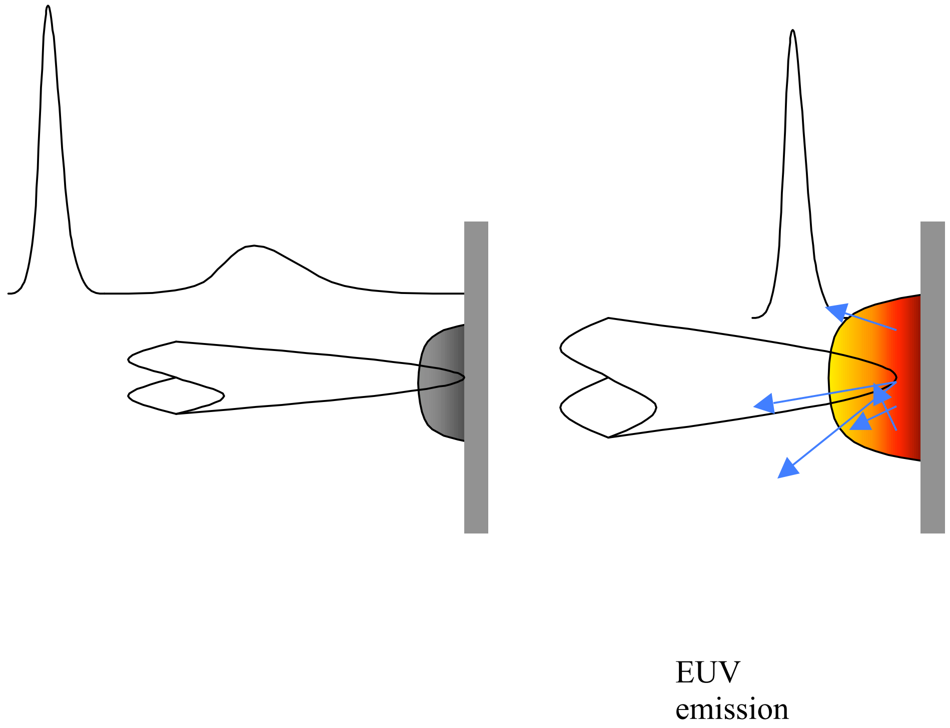
Low-density Sn-based targets have shown comparable or higher conversion efficiency compared with solid density Sn; the reason is also imagined to be due to less opacity [11,12]. And most of the low density Sn-based targets are fabricated using polystyrene templates. Carbon and oxygen atoms play two roles in Sn-doped foam targets. One is to provide a support to low density of Sn atoms. The other is to provide a fast thermal expansion, resulting in lower density of Sn ions. Spectral narrowing has been observed using low density Sn-doped foam targets. The reason comes from less charge state transfer due to less collision in low-density plasma. However, carbon and oxygen do not emit significant 13.5 nm EUV light. And these particles will be accelerated to much higher velocity than Sn ions, which are harmful to optics of EUVL. However, there is no experimental data on their density profile, so it is hard to do simulations to understand their physics directly and accurately.

Another example of the influence of opacity on CE is the dependence of conversion efficiency on wavelength of the driving laser λ. Because critical density is proportional to $1/\lambda^2$, short wavelength can penetrate into higher density, having a better coupling efficiency between laser and plasma. Then it should have a better conversion efficiency than longer wavelength lasers. However, it has been shown that conversion efficiency does not strongly depend on wavelength for solid density Sn [19]. The reason is that the dominant laser absorption and EUV generation region for short wavelength lasers is located in the high density plasma region, in which opacity is much higher than the low density region. The emissivity for short wavelength laser should be much higher than long wavelength laser, but heavier opacity trades off it. So output is not enhanced.

It appears that long wavelength and low-density target are better to achieve high conversion efficiency, CO_2 laser with a wavelength of 10.6 μm is even suggested to act as driver of EUVL source [20]. But if opacity can be reduced by optimized density profile, short wavelength should be better to get higher conversion efficiency due to its high absorption. It is possible to use a combination of short wavelength laser and low-density target to achieve higher conversion efficiency.

Not only ions emitting 13.5 nm EUV light but also ions with lower or higher charger state will absorb 13.5 nm EUV light strongly. So it is possible to optimize the density profile to enhance conversion efficiency. Optimization of the plasma density profile by controlling the laser pulse shape and target form is necessary to improve the conversion efficiency. In order to achieve high conversion efficiency, it is important to generate an EUV EDR located in the coronal region in order to avoid strong opacity in dense region, and to avoid absorption caused by excessively long scale-length plasma.

Laser pulse duration and shape plays a key role in plasma density profile, however it is complicated and costly to shape laser pulses from a commercial laser. Double pulse is an easy and economical way to control plasma density profile. The basic idea is to separate plasma generation and heating processes. A pre-pulse with small energy and low intensity is used to generate plasma, called pre-plasma hereafter. The pre-plasma expands into vacuum. After a suitable delay, a main pulse is employed to heat the pre-plasma to the suitable temperature favorable for 13.5 nm EUV light generation.



(a) Plasma generation (b) Plasma heating

Fig. 2. Principle of double pulse scheme. The processes is separated into two phases: (a)Plasma is generated by a pre-pulse, after an adiabatic expansion, (b) expanded cold plasma was heated by main pulse to a suitable temperature for efficient EUV generation.

The pre-plasma expands isothermally during laser irradiation and adiabatically after turning off the laser [21]. The density profile of pre-plasma can be easily changed by verifying the delay interval between pre-pulse and main pulse. The optimal plasma density profile producing the highest CE can be investigated in a much easier way and with a much lower cost.

Debris from laser-produced Sn-based plasmas includes fast ions, neutral particles, and large blocks. Neutral particles and large blocks come from the interaction of the low intensity part with focal spot, viscosity of ion fluid, the recombination of ions, and the shock impaction from plasma. The yield of ions linearly depends on laser energy. In the double pulse case, debris production only depends on pre-pulse energy. By choosing a suitable pre-pulse energy, minimum ions required to generate efficient EUV light can be produced, such that pre-plasma can act as mass-limited-target. Furthermore, a large amount of neutral particles induced by excessively large energy of the main laser pulse can be significantly mitigated due to the small energy of the pre-pulse. If this double pulse scheme can work as expected, a tape target coated with Sn can be operated at high repetition rate with controllable debris generation, which is much easier and cheaper than other techniques, such as, droplet, liquid jet etc.

The advantages of our proposal include,

1. Density profile can be easily verified by changing the delay interval and pre-pulse laser energy, opacity can be reduced, and higher conversion efficiency can be expected.
2. The number of ion can be controlled by the energy of the pre-pulse. In a mass-limited target, mitigation of debris can be expected.
3. High repetition rate operation is much easier than droplet targets, which need very accurate alignment and synchronization. Higher stability can be expected.
4. Low density Sn ions without any additional and harmful ions. The minimum number of ions required to generates efficient EUV light is generated by pre-pulse. And most of atoms are ionized, ions are much easier to be quenched by applying electric and magnetic fields

Initial target density and additional light ions also can be employed to control the plasma density profile. Low density Sn-doped foam targets and water droplets containing Sn particles are examples. The combination of short wavelength driving laser, low density Sn-doped foam target, and double pulses technology may be a solution to achieve higher conversion efficiency and less debris.

Plasma density profile and comprehensive properties of 13.5 nm EUV light and debris will be investigated in detail.

3. Experimental arrangement and diagnostics

Two lasers will be employed in experiments: One is ps (10^{-12} s) Nd:YAG laser from EKSPLA

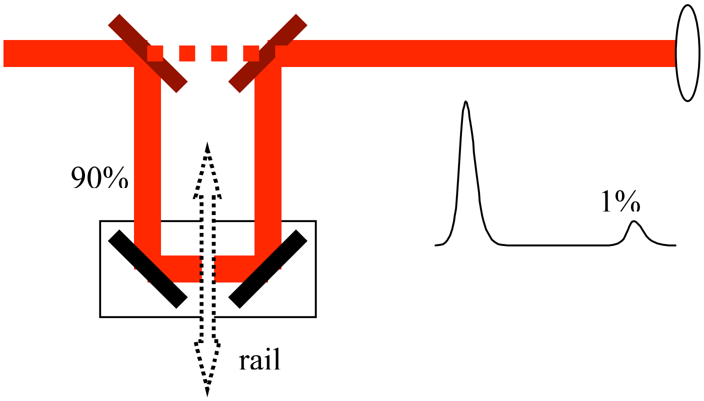


Fig.3 Optical path of double-pulse generation

Company. It produces 1.064 μm laser pulses with energy of 500mJ and pulse duration from 150 to 550 ps. The other is a ns Nd:YAG laser from Continuum Inc., producing 1.064 μm / 650 mJ /7 ns laser pulses. The two lasers can be synchronized with a jitter less than 0.5 ns. Several options will be employed to make double-pulses. The first one uses both lasers; the EKSPLA laser is employed as pre-pulse and the Continuum laser is used as main pulses. Another is the reverse case: ns laser as the pre-pulse and ps laser as the main pulse. Two options are to split ps or ns lasers, as shown in Fig. 3. In that way, the pulse duration of pre- amd main pulses can be varied from 150 ps to 7ns. The delay interval can be varied from 1ns to any long time.

Laser plasma interaction will be performed inside a vacuum chamber with 40 cm diameter and vacuum below 10^{-6} Torr. Focal spot size will be measured by image-relay method, will be kept constantly at 400 μm.

An optical interferometer will be employed to measure electron density profiles in the under dense region. The detail of the experimental arrangement has been given in ref [21].

Conversion efficiency will be measured by a calibrated EUV energy monitor, E-mon from Jena Corp., which consists of a calibrated Zr filter, two near-normal-incident multiplayer Mo/Si mirrors, and a calibrated photodiode. E-mon has a bandwidth similar to practical EUVL systems, 2% centered at 13.5 nm. **A small and simplified EUV energy monitor**, which consists of a Mo/Si multiplayer mirror and a EUV photodiode, will be developed and used to measure the angular distribution of EUV light. The angular distribution of EUV emission from laser produced plasma is not distributed uniform in 2π even at normal incidence, and is different case by case, depending on laser intensity, pulse width, wavelength, target density and specific target form. The general form can be described by $I(\theta)\propto a+\cos^{b}(\theta+c)$. With measured angular distribution, CE can be correctly calculated from E-mon fixed at a particular angle.

Debris mitigation may be the most critical challenge for Sn based targets at present. Characterization and exploration of ways to mitigate debris are very key issues in order to apply them to high repetition rate operation in a practical application. Faraday cup provides spectrum of ions, which reveals some information of plasma, and witness plates provide total debris production including ions and neutral particles, and is an economical way to measure the angular distribution of debris.

Spectrum in soft x-ray range **from 8 to 20 nm will be measured by a transmission Grating Spectrometer (TGS).** Lower density profile means fewer collisions in plasma. It is expected to reduce the ions with low ionization charge state, then highly pure spectrum can be expected. This is important to reduce the heat load of multilayer Mo/Si mirrors used in EUVL system induced by out-band irradiation, and to decrease driver energy. Spectral narrowing arising from fewer collisions and absorption by oxygen ions in low density SnO_2 can reveal information about the plasma density profile.

4. Simulations

4.1 Demonstration simulations of difference between single and double pulses schemes

Plasma density and temperature profiles of laser produced Sn plasmas under the double pulse conditions were simulated by the 1-D hydrodynamic code, Helios [23]. However, because the opacity data of Sn plasma around 30-60 eV is not available at present, detailed atomic and spectroscopic quantities could not be simulated. A Sn planar target is employed to do a demonstration simulation to clarify the feasibility of double pulse scheme. In the simulation, Equation of State (EOS) data was selected from SESAME library, opacity data was selected from PROPACEOS library, and a Spitzer/solid conductor thermal conductivity model was employed. Fluid was treated as two temperatures. Radiation transport was diffusive. Two kinds of laser source were investigated, one is single Gaussion pulse with width (FWHM) of 1 ns as shown in Fig.5. The other consists of double pulse, both with Gaussion shape with width of 1ns. The separation interval was set to 5 ns (peak to peak). Peak intensities of the laser pulses are 1×10^{11} W/cm^2 both for the two heating pulses and 1×10^{10} W/cm^2 for the pre-pulse.

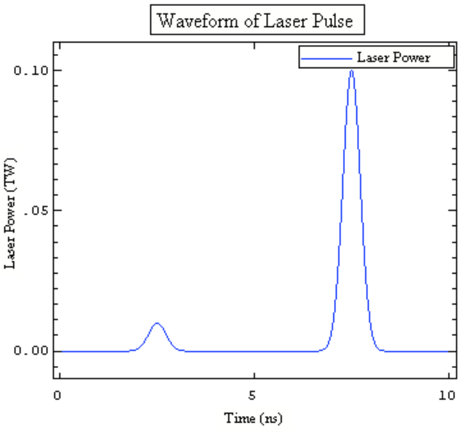


Fig.5. Waveform of double pulses, both pre- and main pulses are Gaussion shape

Typical simulated results of ion number density profile at the peak of pre-pulse, middle point of two pulses, peak of heating pulse in the double pulse scheme and at the peak of pulse in single pulse scheme are given in Fig.4 (a) and corresponding electron temperature profile is shown in Fig.4 (b) respectively. In the case of a single pulse, a very steep density profile was obtained. In contrast, in the case of double pulse scheme, the pre-pulse produce a plasma with several eV temperature, adiabatic expansion after pre-pulse forms a colder plasma with long scale length, a slower slope was formed before the arrival of main pulse, and in the final stage the main pulse heats the pre-plasma to a temperature around 25eV.

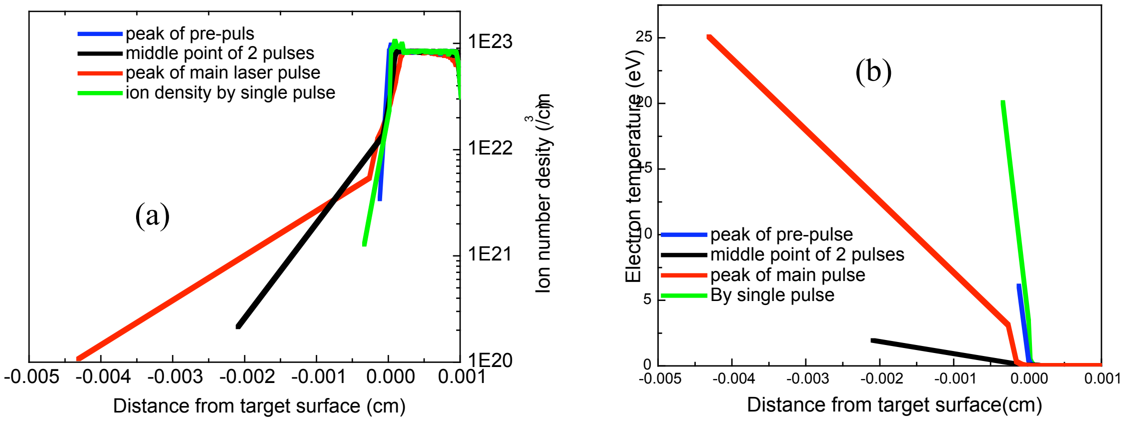


Fig.6. (a) Ion number density and (b) electron temperature profile calculated by Helios under the double pulses and single pulse heating schemes.

It is seen that a higher temperature is observed in the double pulse scheme; this means that more efficient heating of plasma occurs. With a pre-pulse a low density plasma region with long scale length can be generated. Higher CE can be expected arising from efficient absorption and less opacity effect.

Items to be clarified

Evolution of pre-plasma will be investigated, including the influence of pre-pulse energy, and pulse duration on plasma density profile, properties of EUV light (conversion efficiency and spectrum) and debris (production, ion energy spectrum, and angular distribution).

The correlation between plasma density profile and conversion efficiency and debris will be studied by comparing experimental to simulation results containing radiation transport model.

In order to enhance conversion efficiency and to mitigate debris, parameters of laser and target will be optimized by simulation.

5. Expected Results

Clarify the role of density profile in the generation and transport of 13.5 nm EUV light in laser produced Sn-based plasmas. The physics dominating these processes will be understood by the combination of experimental and numerical simulation efforts.

Enhancement of conversion efficiency and mitigation of debris may be expected simultaneously using double-pulses. Optimized plasma density profile will reduce opacity, and mass-limited target controls debris generation.

Progress toward a clear target suitable for high repetition rate operation can be expected. High repetition operation is easily obtained using a rolled tape target with coating of solid density Sn or low density Sn-doped foam.

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