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# Energetic ion emission from periodically modulated metallic surface under intense femtosecond laser irradiation

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**Abstract:** Experimental study on the impact of periodic surface modulations on energetic ion emission from intense laser produced plasma is presented. The targets are excited by intense ($3\times10^{15}$ - $6\times10^{16}$ Wcm$^{-2}$), p-polarized 50 fs laser pulses. The hard x-ray yield representative of "hot" electron temperature is found to be consistently higher for modulated surfaces compared to polished surface indicating enhanced laser energy coupling to plasma. The maximum ion energy measured in keV-MeV range as well as the angle resolved integral ion flux measurements indicate that the surface modulations not only enhance the total yield of ions but increases the maximum ion energy up to 60% compared to polished surface. The surface structuring also seems to influence the divergence of emitted ion beam.

## 1. Introduction

The advent of ultrashort, intense solid state lasers interacting with solids has enabled the production of good quality particle beams with high energy and brightness [1]. Efficient coupling of laser energy in to the matter is of crucial importance to improve the efficiency of these laser driven particle sources. Recent experiments of our group has demonstrated that structuring of the target surface increases the efficiency of laser absorption considerably in terms of the enhanced hard x-ray emission [2]. This is attributed to the surface plasmon assisted absorption of incident laser energy and the local enhancement of electric field because of "lightning rod" effect [3]. As the "hot" electrons are responsible for generation and acceleration of energetic ion emission from the plasma, an enhanced "hot" electron temperature should lead to more energetic ion emission from laser produced plasma. In this context, we present the ion emission from a gold grating surface (Fig. 1c) whose period is smaller than the wavelength of the incident laser radiation. The results were compared with a polished gold surface to investigate the impact of modulated metallic surfaces on the energetic ion emission.

It is well known from Maxwell's theory that normally an electromagnetic wave (EMW) can not excite surface plasmon (SPP) on a metal dielectric interface as the dispersion curve for SPP always lies right to the light curve. The surface roughness provides the required $\Delta\vec{k}$ vector for the absorption to occur. For an arbitrarily rough surface, this can be achieved by various combinations where as for an ordered periodic structure like a grating the condition is fulfilled only when SPP wave vector $\vec{k}_{SPP} = \vec{k}_0 Sin\theta + 2\pi n / d$ where $d$ is periodicity of the sinusoidal grating, $\theta$ is angle of incidence of the EMW on the grating, $\overrightarrow{k_0}$ is incident EMW wave vector and n is an integer. For a grating there exist a critical angle at which the above criteria will be satisfied and EMW will be maximally absorbed by surface plasmon coupling [4].

## 2. Experimental Arrangement

The schematic experimental arrangement is shown in Fig. 1(a). The target is irradiated by 50 fs, p-polarized laser pulse from a 806 nm, Ti-Sapphire laser (THALES LASER, ALPHA 10) with a nano-second contrast ratio of $10^5$: 1 for fs to the ns pedestal, focused by an off axis parabolic mirror in f/4 focusing geometry to a focal spot size of 10 $\mu$m as determined from equivalent imaging technique giving a peak intensity of $10^{15} – 8.0 \times 10^{16}$ Wcm$^{-2}$ within 5% variation. A motorized translation stage assembly ensures that the laser pulse always hits a fresh target region. The targets used in this experiment are (a) gold sinusoidal grating with 1800 grooves/mm and (b) polished gold coated mirror. The grating groove direction is kept perpendicular to the incident laser polarization direction. The angle of incidence of the laser beam is kept 26° [5] with respect to the target normal as this angle satisfies the SPP absorption maxima for the grating used in this experiments. The coating thickness in both the samples is orders of magnitude larger than the skin depth of the laser wavelength. The samples are placed adjacent to each other ensuring identical experimental conditions. With all the components inside the base pressure of the experimental chamber is ~ $10^{-6}$ torr.

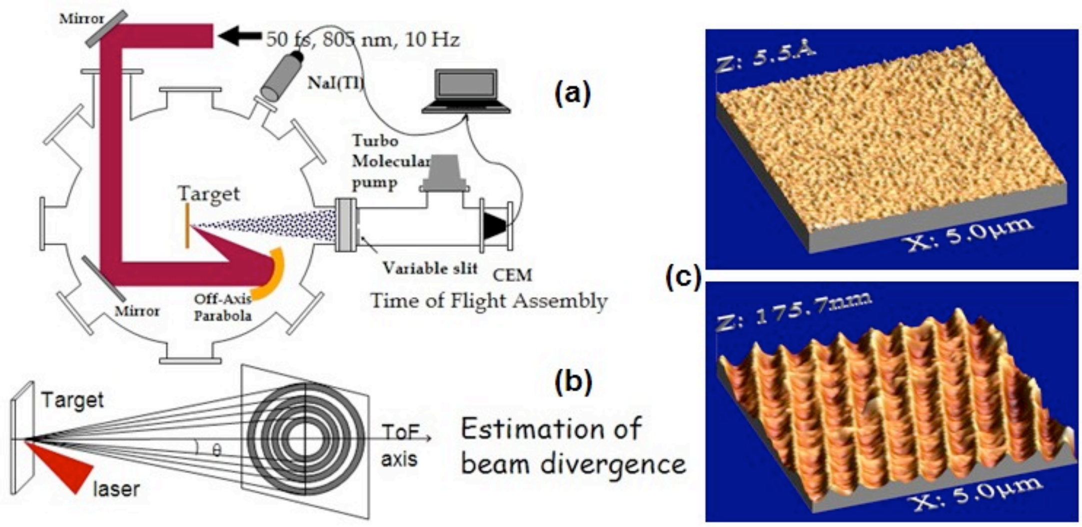


Figure 1: Schematic diagram of the (a) experimental set up (b) annular FCs (AnFC). (c)AFM images of the polished gold surface (Au) and sub- λ grating (AuGR) used in the experiments.

The bremsstrahlung spectra in the 20 - 300 keV energy range is collected by a calibrated NaI(Tl) detector, covered with 15 mm thick layer of lead and gated in time with the incident laser pulse to ensure a nearly background free data acquisition. The signal from the detector is amplified and recorded with a multichannel analyzer connected to computer by RS-232 interfacing protocol. In order to reduce piled up events, the count rate was kept below 0.1 per laser shot by properly positioning the detector and keeping suitable lead apertures in front of it. The ion energy is measured with conventional time of flight (TOF) measurement technique with a channel electron multiplier

(CEM) placed along the target normal at a distance of 97 cm from the plasma spot subtending a solid angle of 26 msr. The TOF assembly is kept at a steady pressure of ~$10^{-7}$ torr by differential pumping to avoid any damage to CEM due to any unwanted avalanche processes. The arrival time information is stored in the computer via 500 MHz digital oscilloscope (YOKOGAWA DL7200) interfaced to the computer following GPIB interfacing protocol. To estimate the angular divergence of the emitted ions form the plasma, four annular faraday cups (AnFCs) placed at angles of 5, 8, 12 and 17 degrees as shown in Fig. 1(b). Each AnFC is made up of 2 mm thick copper sheets and is biased at a voltage of -300 V. A nickel mesh biased at a biasing voltage of -500 V is placed right in front of the AnFC to suppress the secondary electron emission from the Cu sheets used in AnFCs.

## 3. Experimental Results

Fig. 2 shows the bremsstrahlung spectra obtained from the polished gold (Au) surface and sub-λ grating (AuGR) surface with laser incident at an angle of 26° with respect to target normal direction. The measurements were carried out over the same number of laser shots with identical experimental situations. The "hot" electron temperature was estimated by fitting Boltzmann distribution function over the higher energy part of the acquired bremsstrahlung spectra. The acquired bremsstrahlung spectra were then de-convoluted with the transmission factor of the chamber view port. The temperature from the surfaces comes out to be 11 ± 0.6 keV and 26 ± 0.7 keV for Au and AuGR respectively. The ratio of the total bremsstrahlung yield clearly shows that AuGR always yields more x-ray flux although with the increase in laser intensity the relative difference decreases possibly due to the damage of the grating morphology with the very initial part of the laser pulse [2].

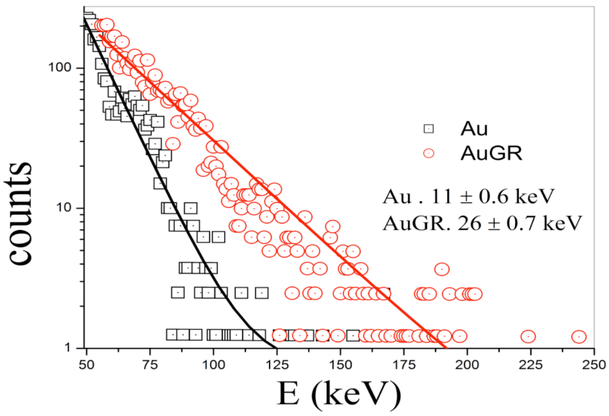


Figure 2: Bremsstrahlung spectra obtained from AuGR and polished Au surface. The "hot" electron temperature in the both the cases are found to be 26 ±0.7 keV and 11 ±0.6 keV respectively.

It is clearly seen from the bremsstrahlung measurement that the modulated surface enhances the laser energy absorption – a result expected on the basis of theoretical predictions and previous experimental observations [3]. The evident question addressed now is whether this leads to enhancement in maximum ion energy as well as total ion flux emitted from the highly dense short lived plasma. The ion energy spectra from the laser produced plasmas from both the surfaces recorded by CEM is shown in Figure 3(a). The ion energy spectra clearly reveals that the ion flux in the higher energy part of the spectrum (>150 keV) is more from AuGR compared to polished Au surface. Similarly, the maximum ion energy ($E_{max}$) obtained from AuGR target is more than that obtained from polished Au surface. Comparison of $E_{max}$ reveals that the maximum ion energy from AuGR always remains higher than that of Au which follows the conventional scaling law ($E_{max}$ ~ $(I\lambda^2)^{0.33 - 0.5}$) dependence quite well.

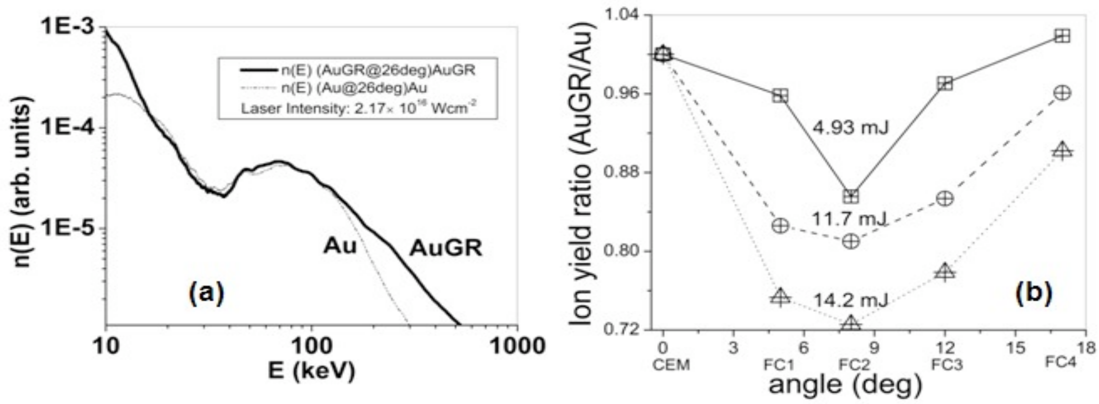


Figure 3: (a) Typical ion energy spectra obtained from AuGR and polished Au surfaces under identical experimental conditions. It is clearly noticed that the number of ions in higher energy side is higher in case of AuGR than polished Au. (b) The ratio of ion flux (AuGR / Au) normalized with respect to flux ratio recorded by CEM as a function of increasing laser intensity.

From the ion flux measurement by AnFCs it is clearly seen that not only that the flux is more in AuGR compared to polished Au surface. Along with that an unintuitive flux distribution is also noticed, as shown in Fig. 3(b). As the laser intensity increases the flux distribution seems to become annular in nature with central branch leading toward the target normal and the other one leading radially outward. Numerical simulations (presented elsewhere) reveals that due to the periodic surface roughness introduced by the sub-λ gratings, the electric field intensity is appreciably enhanced in the vicinity of the grooves leading to an early plasma formation. We believe that the intricate dynamics of this early plasma formation along with the subsequent plasma formation on the rest surface gives rise to the annular ion flux distribution. At present further experimental investigations in this aspect are being carried out.

## 4. Summary

In summary, we have studied the impact of periodically modulated surface roughness on ion emission from intense, femtosecond laser produced plasmas. The study shows that the periodic surface modulations definitely enhances the laser coupling to plasma as well as results in generating higher energetic ions with more flux compared to a conventionally used polished surface. This evidently leads to the possibility of designing new targets that can yield more energetic x-ray and ion sources at sub-relativistic laser intensities.

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