Chapter 2

Short Wavelength Laser

2.1 Criteria for VUV & XUV Laser

In order to realise lasing at shorter wavelengths, numerous approaches had been adopted by the scientific community. For a feasible x-ray laser with significant gain-length, the input power density must be at least of the order of 10^{16} W/cm^2 which is able to produce electron density of 10^{18} cm^{-3} [16].

Although there are numerous ways to produce VUV and XUV radiation, laser produced plasmas seem to be able to deliver the highest brightness, therefore it is generally believed that laser produced plasmas offered the greatest chance of XUV lasing. By irradiating a high peak power optical pulse onto a target material, one might be able to produce the necessary conditions for amplification to occur.

2.2 Laser Produced Plasma

Although vacuum ultra-violet lasing had been successfully demonstrated in the 1970's [17], efforts to push the limit to XUV region seem futile with the then prevailing technology such as electrical discharge and electron beam excitation. One of the hindrance is that the required power density is much higher when compared to what these technologies could provide. The interest for XUV lasing started back in the

1970's, but it is not until 1985 that a clear direction of the research was made. Matthews et.al. of Lawrence Livermore National Laboratory successfully demonstrated lasing of Ne-like selenium in a laser produced plasma using the setup shown in figure 2.1 [5]. Later, Suckewer et al. of Princeton University also obtained

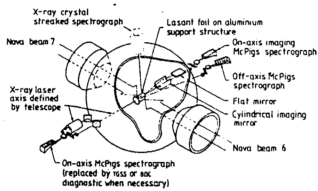

Fig 2.1 Experimental setup LLNL Se x-ray laser showing pumping laser beam and other measuring devices

lasing using a similar method [18]. This technology basically involved focussing an intense high power laser beam onto a solid target and thus heating it up. A high temperature plasma is produced resulting from the extremely high power density, somewhat exceeding 10^{13} W/cm^2. There are two lasing schemes being proposed. One is collisional excitation, which suggests electrons were excited to lasing levels during the heating process. Wheareas the recombination scheme suggests that the incident laser energy has stripped all the valence electrons and excited the atoms. When the atoms are cooling down, different rates of recombinations amongst the different energy states can create a situation which satisfy lasing conditions.

In the neon-like selenium x-ray laser [5], a high intensity beam of 0.53 μm wavelength in 500 psec pulse, populated the 3p level of Se XXV by collisionally monopole excitation. The dipole transition of 3p-3s then gives rise to lasing at about 20 nm wavelength.

The recombination XUV laser is based on transient production of population inversion in a rapidly recombining plasma. The initial state is a hot fully ionised plasma of bare nuclei and free electrons at high density produced by short duration laser pulse irradiation. Hot layer of plasma will cooled adiabatically to a density at which LTE limit is obtained at energy around the n = 3 level, equalibriation above n = 2 level is rapid and n = 2 level is depopulated through Lyman α radiative decays. Population inversion and gain is thus achieved for the n = 3-2 Balmer α transition [16]. In an experiment, a 10.6μm laser pulse of 4×10^9W in 75 nsec pulse was focused to a solid carbon target to form laser plasma which is magnetically confined. The system had managed to produce a *gl* factor of 6 for C VI H_α laser action [18].

Laser produced plasmas though provide significant gain amplification, the setting up of such devices is extremely demanding. High power laser facilities such as NOVA laser and NIKE lasers are needed. This made the research and interest in developing such laser systems limited to large institutions where adequate funding is available. However, to put x-ray lasers into practical and useful applications, one needs a more compact, table-top scheme.

2.3 Electrical Discharge Excitation

Electrical pumping provides a simple means for excitation of atoms and molecules. Electrical discharge involves the setting up an intense electrical field in a gaseous medium between two electrodes. This will cause electrical breakdown of the gaseous medium, thus enabling current to pass through the medium. Electrons that

speed along the discharge path will collide with the medium's atoms and energy transfer occurs between these particles. This will excite the electrons of that particular atom or molecule to higher levels. The higher the discharge current, the higher will the electrons be excited.

Electrical excitation provides a practical means for pumping the population inversion required to achieve stimulated emission. The cost of of setting up a discharge laser, which usually only involves a high voltage charger, capacitors, vacuum pumps and optics, are considerably lower. Various electrical discharge lasers were realised back in the 1960's. Since then, a lot of research had been carried out on such systems and leading to a relatively mature laser technology.

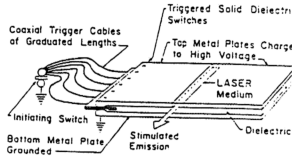

Fig 2.2 Fast travelling wave Blumlein transmission line utilizing parallel plate capacitor and distributed dielectric switches [ref. 21]

Many types of lasers employ this technique as their excitation method. The earliest nitrogen laser and hydrogen laser are the typical systems illustrating the usefulness of such methods. In some cases, current density can go as high as 10 kA/cm^2. This technique also extends to other ion lasers and excimer lasers. In some longitudinal discharge ultra-violet ion laser, the current requirement is even higher, exceeding $20kA/cm^2$ [19]. Unlike other laser which operate at lower pressure, excimer

laser operate at much higher pressure, therefore uniform discharge is of utmost important. The current density of excimer laser is usually lower. However, to obtain uniform glow discharge, preionisation is usually applied [20].

2.4 Hydrogen Laser

The quest for short wavelength laser achieved a remarkable breakthrough in 1967, when Shipman showed the potential of fast discharge in his high voltage travelling-wave pumping of nitrogen laser [21]. His scheme, depicted in figure 2.2 involved using parallel plate capacitors to set up a Blumlein transmission line discharge circuitry. The switching means are solid dielectric switches distributed along the parallel plate which are sequentially fired. Such an arrangement allows fast discharge to take place, due to the extremely low circuit inductance, resulting in high current density.

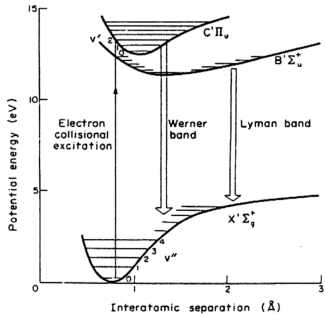

Fig 2.3 Energy level diagram of VUV hydrogen laser showing Werner and Lyman bands lines

With this development, Hodgson [17] and Waynant et.al. [22] independently demonstrated vacuum ultra-violet laser emissions from molecular hydrogen. Lyman band of hydrogen, which correspond to $B^1\Sigma_u^+$ to $X^1\Sigma_g^+$ transition gives rise to lines from 157 nm to 161 nm; whereas Werner band from $C^1\pi_u$ to $X^1\Sigma_g^+$ gives wavelength from 116nm to 124 nm.

However, electrical pumping method do have it's shortfall too. Current density may goes as high as 250 kA/cm^2 only. This is due to the limitation of the circuit geometry and other stringent circuit parameters such as capacitance and inductance. The plasma conditions created in an electrical discharge may sometime be not favourable to pumping conditions. Collisional thermalization by electrons of many low lying energy levels may occur which will not help in population inversion but upset it instead. As a result, only a small portion of electrons are contributing to excite the upper laser level.

Electrical excitation method faced some critical difficulties in efforts to scale to higher output. In order to obtain higher current discharge, higher energy is needed. A straight forward way is to increase the capacitance used, but this will definitely slow down the discharge process. If one scaled the active volume in the channel longitudinally, eventually it may end up with complicated discharge setup, therefore transverse discharge was introduced [23] , which enable volume scaling with much simpler requirement. However, one can not pump in too much voltage in a transverse discharge, as this will result in severe arcing in the discharge.

In some of the 1970's patent documents, efforts by laser researchers to alleviate these difficulties were documented. Beaulieu proposed that the transverse pin discharge, instead of ballasted by resistors, use separate capacitors coupled to the pins to obtain a more uniform discharge [24]. The capacitors are charged up commonly and switched by a common spark gap, however due to its separate coupling to the pins, these capacitors will only dump its energy to their respective pins. However, this particular circuit is too slow for pumping VUV laser.

In another patent by Levine in 1977, a parallel plate Blumlein transmission line was broken up into smaller sections and arranged in such a manner that every small transmission line will discharge separately but the discharge were aligned in a straight line to form a large discharge volume [25]. All the parallel plate capacitors were charged up commonly but the discharge is separated by having separate light-triggered spark gap that are connected to each set of parallel plate capacitor. These spark gaps are filled with trimethyl amine and are fired sequentially when the flashlamp at one end of the spark gap array is triggered. Due to its common charging line, current may not distributed evenly if some of the plates were fired earlier.

Although the above methods had to some extent alleviate the problem of volume scaling, unstable and slow discharge plasmas are some short-comings still prevailing. Such schemes are impossible to discharge in extreme high voltages as coupling of charging device such as a Marx generator is not possible. Furthermore, the electrical isolation between the pins were poor resulted in energy not disributed evenly. Such schemes never made impacts on the development of VUV and XUV lasers due to their inferior operating ratings.

2.5 Requirements Towards Shorter Wavelength

The advent of short wavelength lasers largely depends on the pumping power density. Besides the difficulty that the gain of laser scales as the radiation frequency which had been illustrated earlier. The pumping power of a laser is also inversely proportional to the radiation wavelength [26].

Considering power loss per unit area,

$$P = N_u \ell A_{ul} h\nu$$

$$\geq \Delta N_{inv} \ell A_{ul} h\nu$$

$$= \frac{8\pi}{\lambda^2} \frac{1}{g(\nu)} (\alpha\ell) h\nu$$

Taking $\alpha(\nu) = \frac{\lambda^2}{8\pi} A_{ul} g(\nu)$ and $g(\nu) = \frac{1}{\Delta\nu}\left(\frac{4\ln 2}{\pi}\right)^{\frac{1}{2}}$

We will have

$$P \geq \frac{8\pi h}{\zeta c^2} \nu^4 (\alpha\ell) \frac{\Delta\nu}{\nu} \approx \frac{1.5\text{x}10^{21}}{\lambda^4} (\alpha\ell)\left(\frac{\Delta\nu}{\nu}\right)\left[\frac{W}{cm^2}\right]$$

With N_u = upper level density
l = length of gain medium
A_{ul} = rate coefficient for stimulted emission
h = Planck's constant
ν = frequency
$\Delta\nu$ = line width
$g(\nu)$ = line shape function
$\alpha(\nu)$ = gain coefficient
λ = wavelength

The pumping power requirement will be inversely proportional to λ^4!

Another factor conditioning the realization of short wavelength laser is the fast pumping time requirement. This is due to the inevitably shorter life time of the high

energies upper laser levels. This can be understood from the fact that high energy photons come from large energy gaps, which means the excited state is located much higher than the ground state, which normally has shorter life time.

2.6 Capillary Discharge

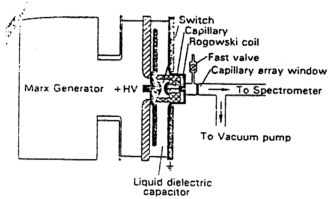

Fig 2.4 Laout of the capillary discharge which obtain amplification of XUV lines. The diagram showed the Marx generator, capacitor, spark gap and capillary setup in a compact design.

For the realisation of table-top x-ray laser scheme, with affordable cost in mind, electrical means still provide the best alternative. Rocca in 1988 proposed a new way by direct electrical excitation to generate plasma conditions favourable of producing soft x-ray laser, which is usually obtainable only by laser produced plasmas [7]. In his subsequent experiments [27], he had successfully demonstrated amplification of XUV lines of 18.6 nm wavelength amplification in C VI using a fast pulsed discharge capillary device. The fast recombining plasma produced from the stripping of outer shell electrons by electron impact is the result of plasma collapse after the initial expansion. Later, Rocca managed to obtain amplification in neon-like argon [28].

Using a careful design of discharge setup, he managed to produced an extremely compact discharge-pumped 46.9 nm laser by collisionally exciting the upper laser level in Ar IX [29]. In his system, the water capacitors are being compactly arranged in a Blumlein transmission line configuration and the power supplied by a four stage Marx generator. He managed to fire 40 kA through a 18.6 cm long capillary in 70 nsec with a charging voltage of 200 kV and resulted in 25 μJ of laser power. This is made possible by the large aspect ratio of the capillary tube. The tube's geometry also provides some form of confinement and rapid cooling to the pinched plasma. These satified the lasing conditions. In 1999, Rocca reported a 1 mJ 46.9 nm Ne-like argon laser, by discharging 26 kA in a 34.5 cm long ceramic capillary tube [30].

2.7 Scalability Limits

It is clearly shown that, for the realization of short wavelength laser, one needs to pump in a lot of energy onto a tiny space. This will ensure high power density to achieve the population inversion. For the realisation of scaling towards shorter lasing wavelengths, the pumping method had moved from straight-forward electrical discharge towards complicated laser produced plasmas. Unfortunately, the schemes employing lasers to produced high temperature plasmas often involved massive installation and extremely high costs. The XUV output is also very little compared to the incident laser power. This made it an impractical and inefficient way to scale to shorter wavelengths and higher output.

Although Rocca's scheme seems promising, it has an inherent difficulty to scale to higher output power. Rocca had to charge up to 200 kV to achieve 26 kA in a 34.5 cm capillary tube for which he obtained 1 mJ of soft X-ray laser output. In order to have higher output power, longer discharge lengths are required, which means higher charging voltage. This leads to technical difficulties. Furthermore, the overall circuit inductance and capacitance will change and will lead to slower discharge current.

2.8 Proposed Works

It is clear that a compact table-top XUV laser system is difficult to realise. Conventional schemes often require massive facilities and huge funding. For this, alternative ways of efficient pumping the XUV laser is much sought after.

In this present project, a novel discharge scheme which could deliver fast high current pulse into the laser channel, and yet offers good scalabilities in term of energy and gain is proposed. The system consists of an array of pin electrodes which will individually breakdown to form high current discharge. An array of pins will create a column of active medium for laser action. The pumping energy could be scaled up by varying the voltage and capacitance of each discharge, whilst the gain could be increased by adding on more electrodes along the array.

Optimization of the scheme's electrical circuitry will be carried out. The effect of various electrical components, including the inductance and capacitance will be investigated. Conditions for better performance will be determined. The aim of the optimization is to obtain, on each and every electrode, a current pulse exceeding 5 kA in a duration shorter than 100 nsec. This will then position the scheme itself as a viable candidate for pumping short wavelength laser.