Chapter 6

Conclusions and Outlook

In this chapter the conclusions from the experiment as well as the main results of the work are summarized. Also, the view on a possible extension of the work on this topic, some suggestions for the next steps and some numerical predictions related to the future experiments are given.

6.1 Main results of the present work

As a main result of this work, the first heavy ion beam pumped UV laser has been successfully demonstrated at the well known laser transition of KrF* excimer at $\lambda = 248 \text{ nm}$ in the experiment, performed at GSI accelerator facility. The laser threshold value of $0.51 \text{ MW/cm}^3$, which corresponds to the ion beam intensity of $1.2 \cdot 10^9$ particles per pulse, has been obtained for this specific cavity setup. Laser action has been clearly proofed by the several independent methods, listed below:

- **appearance of the laser line**
  A strong laser line appeared on the on-axis spectrum as soon as the ion beam intensity became higher than $1.2 \cdot 10^9$ particles per pulse.

- **spectral narrowing of the laser line**
  The spectral width ($W$) of the KrF* laser line in the spectrum registered along the beam axis was almost two times narrower than in the spontaneous emission spectrum, registered perpendicular to the beam axis. However, quantitative analysis of this effect was limited due to a pure optical resolution of the spectrometer.

- **temporal narrowing of the laser signal**
  A different time structure of the spontaneous emission and the laser signals has been observed. The steepness of rising edge of the laser
pulse was higher than of spontaneous emission signal. The maximum duration of the laser pulse was around $87 \text{ ns}$ (FWHM), corresponding to maximum intensity of ion beam pumping pulses, while the duration of spontaneous emission was independent from the beam intensity and was approximately $150 \text{ ns}$ (FWHM) including afterglow processes which is about 40 ns longer than duration of the pumping ion beam pulse.

- **non-linear response of the laser output intensity on the pumping power**
  In contrast to spontaneous emission where the intensity changed linearly with ion beam power, laser emission has showed a clear threshold behavior and non-linear growth of output intensity with increasing number of particles in the pumping pulse.

- **cavity disalignment effect**
  Laser effect in the cavity disappeared if one of resonator mirrors was slightly misaligned and it appeared again when the cavity alignment was restored.

The calibration of the photodiode detectors using commercial KrF$^*$ excimer laser with known laser pulse parameters made possible to conclude the total energy of the laser pulse obtained in the experiment. It was about 2 mJ corresponding to the ion beam intensity of $2 \cdot 10^9$ particles per pulse. From this value a conversion efficiency of the ion beam energy to the laser light of $0.04\%$ has been derived.

Time delays of the onset of the laser emission from the pumping pulse have been measured and analyzed. It was observed that the laser delay was depending on the beam power and it was amounted from 100 ns to 65 ns for ion beam intensities between $1,3 \cdot 10^9$ and $2,5 \cdot 10^9$ particles per pulse correspondingly.

Also within the course of the experiments the dependence of spontaneous emission spectra on the gas pressure in a range of 1.3 ± 2 bar was measured. From this it was concluded that the optimal gas pressure for laser experiments in the sense of laser efficiency is the lowest in observed region.

As a general conclusion of the present work, it could be shown that the intensity, space and time characteristics of ion beams, provided by heavy-ion-synchrotron SIS-18 at GSI are sufficient now to pump gas lasers in UV spectral region.
6.2 Suggestions and outlook for future experiments

As a next step in studying short wavelength lasers pumped with heavy ion beams it is planned to reduce the laser wavelength and to extend the laser experiments into Vacuum-UV range of the spectrum ($\lambda < 200$ nm). Also it is planned to proceed to the excimer lasers of the pure rare gases and to use the so called second continua of rare gas excimers as a laser transition: $\text{Xe}_2^*$ ($\lambda = 172$ nm), $\text{Kr}_2^*$ ($\lambda = 146$ nm), $\text{Ar}_2^*$ ($\lambda = 126$ nm), $\text{Ne}_2^*$ ($\lambda = 83$ nm) and $\text{He}_2^*$ ($\lambda = 80$ nm). These systems are of more fundamental interest than the rare gas halogen lasers because they work with kinetic processes of pure gases. Also, the pure rare gases are technically easier to handle and reduce the safety issues of the experiment. However, these lasers require considerably higher pumping power levels in comparison with rare gas halide excimers, because of the shorter wavelength (for Ne and He cases) and significantly broader laser transition. The emission spectra of the rare gas excimers, observed using low energy electron beam excitation [Fed04], are represented in a Figure 6.1. Some numerical estimations and prediction of the optical gain for the next step of experiments are given in the next paragraph.

Laser action on the second continuum of Ar, Kr and Xe excimers was observed using high energy electron beams for pumping [Hof73, Hug74]. Also

![Figure 6.1: Emission spectra of the pure rare gas excimers.](image)
the spontaneous emission of Ne$_2^*$ and He$_2^*$ excimers has been studied spectroscopically using various excitation methods [Kro89, Fed04], but the laser effect on these transitions is not yet obtained. With intense heavy ion beams it should be possible to pump these lasers under well controlled conditions with optical cavities and high repetition rates compared with electron beam pumping. The homogeneous and well controlled excitation conditions will provide data for correlation between pumping power densities and optical gain, which is in a great importance for development discharge pumped rare gas excimer lasers for commercial and industrial purposes.

In order to study the efficiency for the ion beam induced production of coherent as well as incoherent excimer light quantitatively, it is necessary to obtain detailed information about the absolute values of pumping power densities which can be reached using heavy ion beam pumping. So it is planned to study more carefully the stopping and straggling processes of heavy ions in the laser gas. For this purpose the more reliable diagnostics for ion beam size inside the cavity has to be developed.

The use of heavy ion beams as a pumping source may lead to new pumping schemes on the higher lying level transitions and considerably shorter wavelengths (in the extreme UV and X-ray spectral region), which rely on the high cross sections for multiple ionization of the target species. In the framework of the future facility for antiprotons and ion research named FAIR project it is planned to upgrade the existing accelerators at GSI and build up a new heavy ion synchrotron which will be composed of two rings: SIS-100 and SIS-300. They will be capable to produce heavy ion beams with a magnetic rigidity of 100 Tm for fast extraction and 200÷300 Tm for slow extraction [Hof05]. It is expected that FAIR facility will provide the beams of heavy ions which exceed the current beam parameters up to two order of magnitude by intensity and three orders by the beam power [Tah05a, Tah05b]. Thus, it opens wide perspectives for studying short wavelength lasers and for discovering new laser schemes which could be efficiently pumped only with intense heavy ion beams.

### 6.3 Numerical estimations for future experiments

The experience of the previous experiment has shown that one of the key-problem of heavy-ion-beam pumping is the significant beam straggling in the laser gas cell. This is due to the ions scattering in the laser gas as well as in the intermediate materials between the beamline and the gas cell. As was
mentioned in Chapter 5 the main contribution to the angular spread of the ion beam before entering the cavity was brought in by long (more than 2 m) air section and by thick (3,2 mm) quartz mirror. We can strongly reduce the angular spread of the ion beam at the cavity entry and therefore the beam straggling by decreasing the air gap and the thickness of the entrance cavity mirror. With the present setup it is possible to reduce the air section down to 20 cm without making any changes in the construction. A thin (1,5 mm) Si-wafer can be used as a substrate for the entrance mirror.

In Table 6.1 the energy losses of U-ions in the intermediate materials on a way to the cavity are shown. Calculations were done with the SRIM-code for initial ion energies of 300 and 350 $\text{MeV}/u$. The increasing of the ion beam radius (each radiuses in the case of elliptical beam) after propagation of certain material, estimated with the TRIM-code\textsuperscript{14}, are also given in the table.

\begin{table}[h]
\centering
\caption{Ions energy and increasing of the beam radius in the intermediate materials between the beamline and the laser cavity.}
\begin{tabular}{|l|l|c|c|c|c|}
\hline
Propagated Material & Thickness & \begin{tabular}{c} Ion Energy after propagation (GeV) \end{tabular} & \begin{tabular}{c} Blowing of the ion beam \end{tabular} & \begin{tabular}{c} (for 90\% of particles) \end{tabular} \\
& & \begin{tabular}{c} 300 $\text{MeV}/u$ \small (71,4 GeV) \end{tabular} & \begin{tabular}{c} 350 $\text{MeV}/u$ \small (83,3 GeV) \end{tabular} & \begin{tabular}{c} 300 $\text{MeV}/u$ \small (71,4 GeV) \end{tabular} & \begin{tabular}{c} 350 $\text{MeV}/u$ \small (83,3 GeV) \end{tabular} \\
\hline
Initial ions energy & & & & & \\
Exit Al-window from the beamline & 150 $\mu$m & 70,51 & 82,47 & 58 nm & 46 nm \\
Air gap & 20 cm & 69,87 & 81,87 & 44 $\mu$m & 40 $\mu$m \\
Stainless Steel pressure window & 50 $\mu$m & 69,06 & 81,13 & 27 nm & 23 nm \\
Cavity mirror on Si-wafer & 1,5 mm & 61,05 & 73,71 & 2 $\mu$m & 1,7 $\mu$m \\
\hline
Ion energy at the cavity entrance & & \textbf{61,05 GeV} & \textbf{73,71 GeV} & & \\
\hline
\end{tabular}
\end{table}

To reduce the ion beam straggling inside the laser cell more one can proceed to shorter resonator length (shorter beam stopping length) and higher initial ions energy. But this, of course, will require higher gas pressures. Let us consider a new length of the optical resonator in the region between 40 and 60 cm. In order to pump more energy in the laser gas as well as to decrease the energy loss of the ions in the intermediate materials (and, consequently, to

\textsuperscript{14} The estimations were performed for each material separately without taking into account ion beam straggling in the previous materials. Each calculation had a statistic of 1000 ions and the results, listed in Table 6.1, are valid for 90\% of the particles.
reduce the angular spread of the ion beam at cavity entry) let us increase the initial energy of the ions and consider the cases with 300 and 350 $\text{MeV}/u$.

In Table 6.2 the minimum values for the gas pressure for Xe, Kr, Ar and Ne gases which are necessary to stop Uranium ions with certain initial energy in certain range (in order to fit the resonator length) are given. The present setup can be used with gas pressures up to 10 bar. This limit is defined by the mirror adjustment units (Chapter 4, Fig.4.4) of the laser cavity.

**Table 6.2**: Values for pressure of various laser gases for the cases with different lengths of the optical resonator and different initial ion energies.

<table>
<thead>
<tr>
<th>Initial ions energy</th>
<th>Range of the ions in the gas</th>
<th>Gas pressure (bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40 cm</td>
<td>Xe ($\lambda = 172 \text{ nm}$)</td>
</tr>
<tr>
<td>300 $\text{MeV}/u$</td>
<td>9.7</td>
<td>14</td>
</tr>
<tr>
<td>50 cm</td>
<td>7.8</td>
<td>11.2</td>
</tr>
<tr>
<td>60 cm</td>
<td>6.5</td>
<td>9.3</td>
</tr>
<tr>
<td>350 $\text{MeV}/u$</td>
<td>13</td>
<td>18.5</td>
</tr>
<tr>
<td>40 cm</td>
<td>10.2</td>
<td>14.9</td>
</tr>
<tr>
<td>60 cm</td>
<td>8.6</td>
<td>12.4</td>
</tr>
</tbody>
</table>

It is planned to use the optical cavity only in experiments with Xe and Kr gases for the wavelengths of 173 and 146 nm correspondingly. With the other gases (Ar, Ne and He) the laser could be operated only in ASE (Amplified Spontaneous Emission) mode, since where are no mirrors for these wavelengths ($\lambda < 130 \text{ nm}$) commercially available (at least at the present time). Let us consider two cases for further calculations:

<table>
<thead>
<tr>
<th>Laser gas</th>
<th>Laser wavelength</th>
<th>Gas pressure</th>
<th>Initial ions energy</th>
<th>Resonator length$^{15}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1:</td>
<td>Xe</td>
<td>172 nm</td>
<td>8.6 bar</td>
<td>350 $\text{MeV}/u$</td>
</tr>
<tr>
<td>Case 2:</td>
<td>Kr</td>
<td>146 nm</td>
<td>9.3 bar</td>
<td>300 $\text{MeV}/u$</td>
</tr>
</tbody>
</table>

since they do not require significant changes in the present setup.

The expected sizes of the ion beam inside the cavity could be the following: 2.3 mm (FWHM) at the cavity entry and 9.8 mm and 8.7 mm (FWHM) at the Bragg-peak region for Xe and Kr cases respectively. These

$^{15}$ The distance between cavity mirrors (resonator length) should be bigger than the ions stopping length in the cavity in order to avoid the heating of the exit mirror with the ion beam.
sizes are considerably smaller in comparison with beam sizes which we had in the experiment (6 mm at the entry and around 15 mm at the Bragg-peak region, see Chapters 3 and 5) owing to reducing of the ion beam straggling in the intermediate materials and in the laser gas.

In Figure 6.2 the dependence of the ion beam radius from the penetration depth in the laser gas for the Kr-case is shown. The total beam radius (red curve) is determined by the beam focusing (teal curve) and by the beam straggling (violet curve). The parameters of the beam focusing were used the same as was in the experiment (Paragraph 5.2). The beam straggling in the laser gas was calculated using the TRIM-code.

If we assume the maximum intensity of the ion beam of $4 \cdot 10^9$ particles per pulse (such intensity was obtained at GSI for U-beams in 2003 [Var03], see Chapter 4), the average (along the beam axis) energy density deposited in the laser gas will be $4,1 \frac{J}{cm^3}$ and $4,08 \frac{J}{cm^3}$ for Xe and Kr cases respectively. Which gives $41 \frac{MW}{cm^3}$ and $40,8 \frac{MW}{cm^3}$ of the peak power density for the case of 100 ns (FWHM) ion beam pulse. These values are more than 30 times higher than the maximum value of deposited power density of $1,1 \frac{MW}{cm^3}$ achieved in the experiment (Chapter 5).

Assuming the efficiency of the upper state population $\varepsilon_{up}$ of 10% [Hut80, Sak87] one can obtain the part of the deposited in the gas energy which goes to produce the excimer molecules per time unit and volume unit: $4,1 \frac{MJ}{s\cdot cm^3}$

Figure 6.2: Ion beam envelope inside the gas cell for U-ions with initial particle energy of $300 \frac{MeV}{u}$ in Kr gas (9.3 bar)
and 4.08 MJ/s/cm³ for Xe and Kr cases, respectively. The ionization energies of xenon and krypton atoms are 12 eV and 14 eV, respectively [NIST]. From these values the pumping rate \( R_{lu} \) (a number of upper states produced in a volume unit per time unit) could be concluded: 2.14 \( \times \) 10^{24} s\(^{-1}\)·cm\(^{-3}\) for Xe and 1.82 \( \times \) 10^{24} s\(^{-1}\)·cm\(^{-3}\) for Kr. Since the lifetime of the excimer states are: 5.5 ns for Xe\(_2^*\) [Ket74] and around 6 ns for Kr\(_2^*\) [Koe75, Bon80, Smi83], the spontaneous emission rates will be: 1.82 \( \times \) 10^{8} s\(^{-1}\) and 1.67 \( \times \) 10^{8} s\(^{-1}\) for Xe and Kr cases, respectively (Equ.3.9).

To determine the collisional quenching rate of excimer molecules, let us assume the worst case, when the quenching of the excited states occurs every collision with an atom or a molecule. In this case, the quenching rate will be equal to the average collision frequency \( v_{coll} \), which in turn is defined by the average velocity \( <v> \) and the mean free path \( L_{free} \) of the particles:

\[
v_{coll} = \frac{<v>}{L_{free}}
\]

(6.1)

The average velocity can be found using the following formula:

\[
<v> = \sqrt{\frac{3 \cdot R \cdot T}{M}}
\]

(6.2)

where:
- \( R \) – molar gas constant,
- \( T \) – gas temperature,
- \( M \) – molar mass of the rare gas,

so for the room temperature it is 238 m/s and 298 m/s for Xe and Kr cases, respectively. The mean free path is calculated using the following formula:

\[
L_{free} = \frac{0.707}{\pi \cdot d^2 \cdot n}
\]

(6.3)

where:
- \( d \) – diameter of the rare gas atom,
- \( n \) – concentration of atoms (density),

it is approximately 0.52 µm for the Xe case and 0.56 µm for the Kr case. Thus, the estimated in this way collisional quenching rate is 4.6 \( \times \) 10^{8} s\(^{-1}\) and 5.3 \( \times \) 10^{8} s\(^{-1}\) for Xe and Kr cases, respectively.

Thereby, the upper state population \( N_u \) for Xe case will be 3.33 \( \times \) 10^{15} molecules per cm\(^3\) and for Kr case – 2.61 \( \times \) 10^{15} molecules per cm\(^3\) (Equ.3.7) The stimulated emission cross section \( \sigma_{st} \) for Xe\(_2^*\) is assumed to be 1.5 \( \times \) 10^{-17} cm\(^2\) and for Kr\(_2^*\) it can be estimated around 10^{-17} cm\(^2\) [Hut80]. The photons emitted by Xe\(_2^*\) as well as by Kr\(_2^*\) molecules have sufficient energy.
to ionize other excimers (Xe\(_2^*\) and Kr\(_2^*\), respectively), thereby reducing the gain of the laser. The cross section of this photoionization process is estimated to be \(2 \cdot 10^{-18} \text{cm}^2\) for Xe\(_2^*\) and around \(10^{-18} \text{cm}^2\) for Kr\(_2^*\) [Hut80, Eck88]. Thus, by taking into account the photoionization as a competitive process to the stimulated emission, the small signal gain \(g_{ss}\) is predicted to be about 4.3% per cm and about 2.3% per cm for Xe and Kr cases, respectively.

Assuming the length of the active medium in the resonator of 60 cm (range of the ions in the laser gas) for both cases, and using the highly reflective cavity mirrors with reflectivity of 96% for \(\lambda = 172\ \text{nm}\) (Xe case) [Eck88], and about 85% for \(\lambda = 146\ \text{nm}\) (Kr case) [Sas01], one can obtain the net gain \(g_{net}\) per single trip of 2.54 for the Xe\(_2^*\) and 1.22 for the Kr\(_2^*\), respectively. Since for 100 ns pumping pulse one can assume around 42 single trips, the clear laser action can be expected for both cases.

Over the last few years there were a number of works, reported about the laser action in pure rare gas excimers achieved using the discharge and the electron beam pumping [Eck88, Koc95, Nee96, Sas01]. Kochetov and Lo in they work [Koc95] achieved the power deposition with a self-sustained discharge up to 13 MW/cm\(^3\) in binary mixtures of Xe/Ne and Xe/He and a net gain of the Xe\(_2^*\) laser up to 4.5% per cm. In 2001 Sasaki et al. had demonstrated the Kr\(_2^*\) laser oscillation with the self-sustained discharge pumping of the pure Kr at 10 bar pressure [Sas01]. They obtained the net gain coefficient of 1.1% per cm and the deposited power of more than 20 MW/cm\(^3\) was estimated. Thereby, with our estimations, we definitely can expect the successful laser action for both Xe and Kr cases.