Master of Science Thesis

Experimental study of a Thomson parabola Ion Spectrometer as a diagnostic tool for CERN Laser Ion Source

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Abstract

The plasma produced when a powerful laser pulse is focused onto a target surface in vacuum can provide a copious source of highly charged ions. Ions can be extracted from the plasma to form a high current, short pulse length ion beam. A Laser Ion Source (LIS) is an option for the injection system of heavy ions for the Large Hadron Collider at CERN. The charge-state and energy distribution of the ions from a LIS are typically measured using the Time-of-flight method. This is possible since the creation time of the plasma is short compared to the plasma pulse length. A Thomson parabola Ion Spectrometer (TIS) uses both electric and magnetic field deflection and a 2D spatial detector to resolve the E/z and P/z phase spaces. Therefore a full energy and charge-state distribution can be obtained from one pulse. This report presents some results of measurements performed with a TIS on CERN LIS and a discussion of the suitability of a TIS as a diagnostic tool in this environment.
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Chapter 1

Introduction

1.1 CERN

CERN is situated in the beautiful countryside at the foot of the Jura mountain on the Swiss-French border near Geneva. The surrounding villages with their typical old French style does not reveal that this is the site for the worlds largest research centre for experimental particle physics.

The organisation was founded in September 1954 by twelve West European states. The aim was to provide for collaboration among European States in pure scientific research on the innermost constituents of matter. It has now grown to be 19 collaborating member states; Austria, Belgium, Czech republic, Denmark, Finland, France, Germany, Greece, Hungary, Italy, Netherlands, Norway, Poland, Portugal, Slovak republic, Spain, Sweden, Switzerland and United Kingdom. It is through financial contributions from them that CERN can fund its projects. The annual budget is 937 million Swiss francs (1996) or about 5 billion Swedish kronor. Out of this Sweden pays almost 150 MSEk or 2.6%.

Israel, Japan, the Russian Federation, Turkey, the European Commission and UNESCO are states with observer status. All together there are about 6500 scientists representing 500 universities from more than 80 nations participating in the experiments.

The acronym CERN comes from the earlier French name “Conseil Europeen pour la Recherche Nucleaire”. The official name is now “The European Laboratory for Particle Physics”.

The first proton beam was accelerated at CERN on 1st August 1957 in a Synchro-cyclotron. After this many improvements and discoveries have been made. Today research is carried out on three circular accelerators; Proton Synchrotron (PS), Super Proton Synchrotron (SPS) and Large Electron Positron collider (LEP). This research gives us an increased knowledge about fundamental particles but also a better understanding of how the Universe is constructed. The infinitesimally small world of the fundamental particles and the (almost) infinitely large Universe are very closely related.

Physicists working at CERN has been rewarded the Nobel prize three times:
1993: George Charpak for his invention and development of particle detectors, in particular the multiwire proportional chamber.
1988: Jack Steinberger for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino. He had two co-authors Leon M Lederman and Melvin Schwartz, who did not work at CERN.
1984: Carlo Rubbia and Simon Van Der Meer for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction.
1.1.1 Particle accelerators and detectors

There are two kinds of accelerators; linear and circular. Linear accelerators are limited by their length and can only accelerate particles to some MeV per mass unit (u). In the circular accelerators particles can be accelerated to almost the speed of light (some hundred GeV/u). Here the particles gain energy by passing electromagnetic cavities, resonating at microwave frequency.

The particles travel in bunches, focused by magnetic optics and in the circular accelerators they are also steered using magnetic fields. When the particles have been accelerated to the required speed (or energy) they are made to collide. They can be collided into fixed targets, this is usually ions, or into other accelerated particles.

Colliding beam accelerators, also called colliders, use two beams (consisting of several bunches of particles) circulating in opposite directions. If the beams consist of particles and their partner anti-particle, the particles will have the exact opposite motion for the same magnetic field. It becomes more complicated when equally charged particles (such as ions) are to be collided. Then they have to be accelerated in separate magnetic channels.

The particle beams are made to collide at certain points of the ring. Here large detectors are placed to record what happens at the collisions. Not all of the particles in the beams collide. It is actually only a fraction of all the particles that collide each time the beams meet. The event rate, or luminosity (particles/cm²/s), characterise the collider together with the energy it can accelerate the particles to.

When the particles collide the energy from both particles is concentrated into a very small region of space and a high energy density is produced. From this new particles can be created according to the relation between matter and energy (E = mc²) and the remaining problem is to detect them. This is done using particle detectors made of several different parts, each specialised to measure different properties of the particle.

The particles accelerated in the CERN accelerators are electrons and positrons, protons and antiprotons, and ions. A scheme of the accelerator complex is shown in Figure 1.1.1. The Antiproton Accumulator Complex (AAC) was constructed 1981 to produce high intensity antiproton beams and the PS and SPS became the world's first matter-antimatter colliders. It also made it possible to produce anti-hydrogen in the Low Energy Antiproton Ring (LEAR) that was constructed not long after the AAC. In 1996, the AAC was shut down because of budget cuttings and the LEAR was converted to the Low Energy Ion Ring (LEIR).

Today the largest accelerator at CERN is the Large Electron Positron collider (LEP). It is 27 km in circumference and built in an underground tunnel varying in depth between 50 and 150 m. It was built (came into operation 1989) to produce and study W and Z particles, carriers of the fundamental weak force. After this was successfully achieved, LEP was upgraded to LEP2 by gradually replacing the copper cavities with superconducting ones. The final centre-of-mass energy for LEP2 will be 190 GeV, planned to be obtained in 1998.

The main reason to accelerate and collide particles is to find out how matter is built, what are the forces and the elementary particles, and to explore two of the fundamental questions of physics; What happened at the beginning of time, the Big Bang, and How has the Universe become as the one we see around us today.

According to the Standard Model, there are four fundamental forces; Electromagnetic, Weak, Strong and Gravitational. These forces are transmitted between the building blocks of matter by force carriers. The building blocks, quarks and leptons, are the most fundamental particles because so far no internal structure has been discovered.
1.2 CERN Large Hadron Collider

The CERN Large Hadron Collider (LHC) is under construction now and is planned to be started up in 2004. It will accelerate protons and heavy ions to higher energies than has ever been done before. The protons will be collided at centre of mass energy of 14 TeV and the heavy ions at centre of mass energy of 1150 TeV [1]. The energy density provided by the heavy ions is as high as the one at the first $10^{-12}$ second of the Universe's life. This corresponds to a temperature of $10^{16}$ K and will make it possible to study the very early Universe.
The LHC will be built in the same tunnel that now hosts LEP and the same pre-accelerators will be used. Since the LHC will accelerate heavy particles (compared to electrons), but will have the same radius as the LEP, it will need higher magnetic fields to bend the beam. The bending dipole magnets will need a field of 8.4 T which can only be obtained by superconducting technology. To cool the magnets superfluid helium at 1.9 K will be used [2].

With these high energies, LHC will make it possible to find new physical phenomena. The planned experiments are designed to look for theoretically predicted phenomena such as the Higgs boson and the lightest Super Symmetric (SUSY) particle(s). If the Higgs boson exists and is found, it will experimentally prove the existence of the Higgs mechanism and the origin of mass could be explained. The SUSY theory predicts that each known particle has a supersymmetric partner. This is a popular idea suggested by the unification of the four forces acting on matter. Another question that could be answered, at least partly, is why there seems to be no antimatter left in the Universe.

To catch all the information when the LHC’s beams collide, very large detectors are needed. Atlas\(^1\) and CMS\(^2\) are two detectors being built to study proton collisions. The main tasks are here to look for Higgs bosons and SUSY particles. At LHC-B a study of Charge-Parity (CP) violation in B-meson decays will be made. ALICE\(^3\) is the detector that will record what happens when lead nuclei are collided and creates Quark Gluon plasma.

### 1.3 Background

The source that provides the heavy Pb\(_{28}\) ions today is an Electron Cyclotron Resonance (ECR) source. It uses microwaves (14.35 GHz) to heat the electrons in a plasma at the electron cyclotron frequency, forced by the magnetic field from two solenoids around the plasma chamber. The high energy electrons then cause step-wise ionisation of the ions within the plasma. The output current from the source is 80 \(\mu\)A of lead 27+ ions in a 1 ms pulse [3].

This pulse is, after initial acceleration in an RFQ and a linear accelerator (linac), stripped to 53+ and multi-turn injected into the PSB [4]. Ie. the beams are stacked many times on top of each other. Each of the four storage rings of the PSB is sequentially filled with 17 ion beam turns. The beam is then bunched to four bunches in each ring and further accelerated before it is injected into the PS. After the PS the ions are fully stripped (82+) and the Pb nuclei are passed on to the SPS where the final energy in is 170 GeV/u. Then the fixed target experiments are performed.

The multi-turn injection stacking is only 50% efficient [4] and with an inherent increase of emittance (the phase space area of the beam, see section 2.4), it results in a considerable decrease of beam luminosity. If this ECR source was to provide ions for the LHC, the beam would have to be accumulated in the Low Energy Ion Ring (LEIR) and there be cooled using electron cooling. The cooling would decrease the emittance (see Appendix D) and thereby increase the luminosity. This is an expensive scheme, since the LEIR only is required for heavy ions.

A possible alternative to this scheme is a laser ion source. It could provide 6 mA of lead 25+ ions in a 6\(\mu\)s pulse [5]. This only needs a single-turn injection in the PSB, and would satisfy the luminosity requirements of the LHC without using the LEIR.

---

1 A Toroidal LHC Apparatus  
2 the Compact Muon Solenoid  
3 A Large Ion Collider Experiment
1.4 Purpose of this study

To prove that a Laser Ion Source (LIS) is a feasible solution for LHC injection, it is necessary to determine the beam quality. This is done measuring the charge-state distribution (CSD), energy distribution of the charge-states, current density, emittance, and energy spread of the beam.

The CSD and energy distribution are usually measured using an electric or magnetic spectrometer together with a time resolved detector, typically a Secondary Electron Multiplier (SEM). To get a full distribution, a large number (50 - 100) of pulses must be measured, since the energy spread of each charge-state is of the order of ΔE/E – 1.

A Thomson parabola Ion Spectrometer (TIS) uses both electric and magnetic field deflection and a 2D spatial detector to resolve the E/E and P/P phase spaces. It is therefore possible to measure a full energy and charge-state distribution in one pulse.

The aim of this work was to measure the beam produced by the CERN Laser Ion Source with a TIS from the Czech Academy of Science, Prague. Efforts were then made to produce quantitative results of the beam charge-state and energy distributions. From this point the suitability of a TIS for measurements on the CERN LIS could be assessed.

1.5 Outline of the Thesis

Chapter two will help the reader to understand the function of the instruments used in the experiments. It introduces some of the terminology used for Laser Ion Sources, but only enough to follow the discussion later in the thesis.

Chapter three presents the CERN Laser Ion Source, the elements and what measurements are done to characterise the source. This chapter contains a lot of technical data and theory about the source, which can be intimidating for readers without experience of ion sources and particle detection. However, this is necessary information for someone who wants to compare it with other ion sources.

In the fourth chapter, the Thomson Parabola Ion Spectrometer (TIS) is presented, including information about the TIS construction and how the data about the plasma is achieved. The chapter also contains information about which quantities of the plasma were analysed with the spectrometer and how the analyses were made.

The chapters five and six contains the results from the experiments with ion plasma and accelerated ion beam, respectively, while the discussion of the results is given in chapter seven. Here is also a list of all the possible sources of errors that can have been made during the measurements.

Finally, in chapter eight, are the conclusions that could be made. This chapter includes a summary of the measurements done and the key results, some suggestions for improvements and possible applications of a TIS at CERN Laser Ion Source.

1.6 Acronyms and symbols

1.6.1 Accelerators

AAC - Antiproton Accumulator Complex
LEAR - Low Energy Antiproton Ring
LEIR - Low Energy Ion Ring
LEP - Large Electron Positron collider
LINAC - Linear Accelerator
PS - Proton Synchrotron
PSB - Proton Synchrotron Booster
SPS - Super Proton Synchrotron
1.6.2 Variables and constants

$\alpha, \beta$ - geometric constants
$\gamma$ - angle
$\delta$ - secondary electron factor
$e$ - emittance
$\phi$ - transparency of grid
$\phi$ - diameter of hole
$\sigma$ - transition cross section
$\Psi$ - deflection angle
$B$ - magnetic field
$B_0$ - magnetic field value
$v$ - velocity of light in vacuum
$d$ - distance
$E$ - electric field
$E$ - energy
$E_i$ - ion energy
$F$ - force
$F_0$ - photon flux
$I$ - intensity
$I$ - current
$I_M$ - magnet current

1.6.3 Acronyms

CCD - Charge Coupled Device
CSD - Charge-State Distribution
EM - Electromagnetic
ESA - Electrostatic Analyser
FC - Faraday Cup
FWHM - Full With Half Maximum
IC - Ion Collector
LEBT - Low Energy Beam Transport
LIS - Laser Ion Source
MCP - Micro Channel Plate
MM - Multi Mode

1.6.4 Units

$1$ e (elementary charge) = $1.602 \times 10^{-19}$ C
$1$ eV (electron volt) = $1.602 \times 10^{-19}$ J
$1$ Gauss = $10^{-4}$ Tesla
$1$ mbar = $10^2$ Pa = $0.75$ torr
$1$ u (unit mass) = $1.66 \times 10^{-27}$ kg
$m$ - milli ($10^{-3}$)
$\mu$ - micro ($10^{-6}$)
$n$ - nano ($10^{-9}$)
$V$ - volts
$A$ - ampere

$J$ - current density
$L_1, L_2$ - length
$m_i$ - ion mass
$N_i$ - number of atoms
$n_i$ - ion density
$P$ - momentum
$p$ - pixel number
$P_i$ - ion momentum
$Q$ - total charge
$r$ - radius
$R$ - resistance
$S$ - area
$sec$ - second
$t$ - time
$U$ - potential
$v$ - velocity
$V_{el}$ - voltage over condenser plates
$V_k$ - kinetic energy
$x, y, z$ - direction
$z$ - charge

MO - Master Oscillator
PA - Power Amplifier
PD - Power Density
RIC - Ring Ion Collector
RMS - Root Mean Square
SEM - Secondary Electron Multiplier
SM - Single Mode
TEA - Transversely Excited Atmospheric pressure
TIS - Thomson parabola ion Spectrometer
TOF - Time-of-flight
Chapter 2

Introduction to laser ion sources

This chapter will clarify the terms used and instruments mentioned in this report. It will not explain everything about laser ion sources but give an introduction to laser produced plasma and the important properties of a laser ion source. For a more detailed discussion see references [6]-[12].

2.1 Laser

The word laser is an acronym for Light Amplification by Stimulated Emission of Radiation. It is however, commonly used not only for frequencies of visible light, but for all frequencies from infrared to the x-ray region. These lasers can sometimes be called infrared, ultraviolet or x-ray laser, respectively, to make a distinction. The most outstanding properties of a laser beam are its high degree of directionality, monochromaticity, coherence and brightness [6].

A laser exploits three fundamental phenomena which occur when an electromagnetic (EM) wave interacts with a material. These are the processes of spontaneous and stimulated emission and the process of absorption. In the spontaneous emission process, an atom in the material decays from a higher energy level (level 2) to a lower (level 1) through the emission of a photon. In the stimulated process an incident photon, with a frequency equal to the atomic frequency in the material, stimulates the $2 \rightarrow 1$ transition. Then there will be two photons with the same phase and direction. In the absorption process, the incident photon is simply absorbed to produce the $1 \rightarrow 2$ transition. The simulated emission and the absorption are characterised by the photon flux $F$ (corresponds to the intensity of the EM wave) and the transition cross section $\sigma$.

The number of atoms, per unit volume, that occupy a given level $i$ is called the population of that level and is denoted $N_i$. In the case of thermal equilibrium, the energy level populations are described by Boltzmann statistics. If $N_2$ and $N_1$ are the thermal equilibrium populations of two levels, we have:

$$\frac{N_{e2}}{N_{e1}} = e^{\frac{(E_2 - E_1)}{kT}} \tag{2.1}$$

where $k$ is Boltzmann's constant and $T$ the absolute temperature of the material. This shows that, when the energy difference is greater than $kT$, we have $N_2 < N_1$.

If the material is to behave as an amplifier, the population needs to be inverse, i.e. $N_2 > N_1$. Otherwise the elemental change of flux, for a plane wave travelling a distance $dz$ in the material, would become negative (equation 2.2). The intensity would decrease instead of increase.

$$dF = \sigma F (N_2 - N_1) \cdot dz \tag{2.2}$$

A material having a population inversion is called an active medium. By placing the active medium between two highly reflecting mirrors, a plane EM wave, travelling in a direction orthogonal to the mirrors, will bounce back and forth between the mirrors and be amplified on each passage through the active material. If one of the mirrors is partially transparent, a useful output beam can be extracted.
The oscillation will start when the gain of the active material compensates the losses in the laser (i.e. the output coupling). Since the gain is a function of the population inversion, the threshold is reached when \((N_2 - N_1)\) reaches a critical value, known as the critical inversion. Once the critical inversion is obtained, oscillation will build up from the spontaneous emission, which will lead to stimulated emission.

To obtain a population inversion with means of EM radiation, at least three levels are needed in the given atomic system. With only two levels, the system would absorb the radiation until the populations are equal \((N_1 = N_2)\). Then the absorption and stimulated emission would compensate each other and the material would become transparent.

In a three-level laser (Figure 2.1-1 a), the atoms are in some way raised from the ground level 1 to level 3. If the material is such that, after an atom has been raised to level 3, it decays rapidly to level 2, then a population inversion can be obtained between levels 2 and 1. In a four-level laser (Figure 2.1-1 b), atoms are raised from ground level 1 to level 4. If the atom then decays rapidly to level 3, a population inversion is obtained between levels 3 and 2 this time. Once the oscillation starts in this kind of four-level laser, the atoms will be transferred to level 2. For a fast operation it is then necessary that the transition 2 \(\to\) 1 is very fast.

![Diagram](image)

*Figure 2.1-1: a) Three-level and b) four-level laser schemes.*

The four-level laser is preferable, since the population inversion between levels 3 and 2 is easier to obtain that that between levels 2 and 1. In the beginning almost all atoms are in ground level 1. When the pumping (excitation of the atoms) starts, the atoms will be raised to level 3 and 4, respectively, and then immediately drop one level. In the three-level laser more than half of the atoms must be in level 2 to create a population inversion. For the four-level laser there will be a population inversion as soon as one atom is in level 3, since level 2 from the beginning is empty.

### 2.1.1 CO₂-laser

One of many kinds of lasers (YAG, Iodine, Neodymium,...) is the CO₂-laser. This laser uses a mixture of CO₂, N₂ and He gases. It is a four level laser, where the oscillation takes place between two vibrational levels in CO₂ while N₂ and He greatly improve the efficiency of the laser action [6].

The upper laser level in CO₂ is efficiently pumped by two processes, electron collisions and energy transfer from N₂ molecules. The N₂ molecule is itself excited by electron collisions, to a vibrational level that is metastable. Because the level is metastable and close in energy to the upper laser level in CO₂, the energy transfer can easily take place.

As discussed above, the performance of the laser is very dependant on the decay time of the lower laser level. In the case of a CO₂ laser this is greatly influenced by the presence of He. Another big advantage with the He is that, because of its high thermal conductivity, it helps to keep the CO₂ cold by conducting heat away from the walls. A low CO₂ temperature is necessary to avoid population of the lower laser level by thermal excitation.
From their way of construction, CO₂ lasers can be separated into five categories:

- lasers with longitudinal gas flow
- sealed lasers
- transverse flow lasers
- transversely excited lasers (TEA)
- gas-dynamic lasers

The main reason for flowing the gas mixture is to remove the dissociation products, in particular CO, which would contaminate the laser. Complementary, the flowing contributes to remove the heat from the gas mixture. Otherwise the heat removal is effected simply by diffusion to the walls of the laser, which are cooled. The sealed lasers survives by adding a little H₂O to the gas mixture. This leads to regeneration of CO₂ [6].

The most efficient way to flow the gas is transverse to the resonator axis. In the lasers with longitudinal gas flow, the output power can be saturated due to the heating. There is an optimum value for the pressure in that kind of laser. The higher the pressure, the more power is dissipated in the gas and causes heating, but with lower pressure there will be less active medium and therefore less output power. In the lasers with transverse gas flow, the problem with heating is taken care of, if the flow rate is high enough.

The gas mixture is pumped by an electrical discharge. With a longitudinal discharge, an increase in pressure requires a corresponding increase of discharge voltage. This difficulty can be overcome with a discharge perpendicular to the resonator. In this way, the pressure can be as high as atmospheric and still give a good input to output power ratio. These lasers are therefore called Transversely Excited Atmospheric pressure (TEA) lasers. An example of a TEA laser is shown in Figure 2.1-2.

![Diagram of a TEA laser](image)

**Figure 2.1-2: Schematic diagram for a TEA laser.**

In the gas-dynamic laser, population inversion is not produced by an electrical discharge but by rapid expansion of a gas mixture which has initially been heated to a high temperature. The time for expansion is short compared to the lifetime of the upper laser level but long compared to the lower. During the expansion, the pressure and the temperature decreases drastically. In this situation, the upper laser population remains at about the same value as in the hot gas mixture, while the lower laser population decreases to the value corresponding to the lower temperature.

### 2.2 Laser-target interaction

When a powerful laser pulse is focused onto a metal surface, the solid absorbs laser radiation, leading to localised heating and evaporation of the metal. Electrons in the cloud of vaporised material absorb laser radiation by inverse Bremsstrahlung and cause stepwise ionization of the metal atoms. After a
short time (nanoseconds) the plasma reaches a critical density and the absorption of laser radiation increase dramatically. This causes the plasma electron temperature to rise drastically and the plasma becomes highly reflective to incoming laser light. The very hot dense plasma formed by this process undergoes a rapid expansion normal to the target surface and the ions obtain a range of kinetic energy [7,8].

The character of the plasma is a strong function of the laser power density that hits the target. For higher power densities the metal atoms will be more ionized and obtain a higher initial kinetic energy. The maximum ion charge-state produced by laser-target interaction is determined by the electron temperature, since this sets the maximum ionization energy achievable by plasma electrons [13].

2.3 Extraction

A very important part of ion sources is the extraction. The trajectories of the accelerated ions, which determine the beam quality (for example emittance, Appendix D), are influenced by several factors, such as applied field strength, shape of the emitting surface and space-charge density of the resulting beam itself. The general case discussed here implies positive ions generated from a quasineutral plasma, and apertures that are circular.

The extraction process consists of applying a high voltage between an ion reservoir and a perforated acceleration electrode. The emitting surface, or meniscus as it is called in the case of plasma sources, is shaped in the aperture of the electrode. The shape depends on the electrical field distribution due to the applied boundary conditions and the local densities of plasma ions, electrons and accelerated ions [7]. See Figure 2.3-1 for three different types of menisci. Ideally, the meniscus should be slightly concave [13]. If the plasma density is fixed, the meniscus shape can be altered with the applied voltage and/or the distance between the electrodes.

![Figure 2.3-1: The meniscus acts as a boundary layer between the plasma and the accelerated ions. Three cases of ion extraction a) overdense plasma, b) medium dense plasma, c) underdense plasma. Always in comparison to the applied extraction field. P means plasma, O outlet electrode and E extraction electrode.](image)

When the beam, now consisting of only ions, is drifting in the beam transport line, it will inevitably collide with the walls and release molecules. These molecules, also called residual gas, can interact with the ions and become ionised. This way there will be three kinds of particles from the residual gas; molecules, ions and electrons. The molecules are stable and will not interfere with the ion beam. The electrons can reduce the space charge, which is good but can lead to falsely low ion currents, while the residual gas-ions can screen the accelerated ions, which is not good.

The electrons must be kept from being accelerated back into the source, since that would intrude the fragile relation between the plasma and the ions at extraction. The shielding can be achieved by means of a so-called acceleration/deceleration system, where a screening, or suppressor, electrode is introduced into the main extraction gap (Figure 2.3-2). The introduced electrode is biased to a sufficiently low potential to create a negative potential well and form an electron trap. Then the
electrons in the plasma will be stopped at the extraction electrode, and give the true target current, and the electrons from the residual gas will be stopped at the suppressor electrode.

![Diagram of laser ion source](image)

*Figure 2.3-2: The acceleration/deceleration system is needed to keep electrons from being accelerated back into the source. Also seen in the figure is the potential distribution along the system axis z.*

This is a rather unsophisticated system. In further developed systems, there are electrodes designed to shape the ion beam and give it special properties. That will not be discussed here, since the source used for the experiments did not have any special facilities. The interested is recommended to read reference [7] chapter 3.

### 2.4 Spectrometers

Spectrometers, or spectrographs, are used to detect and identify particles. There is a small difference between a spectrometer and a spectrograph. The first uses an electrical method of detection and the second detects the particles by a photographic plate. Otherwise there are no differences, they can use the same means to separate the particles. Therefore only the term spectrometer will be used here.

There are many kinds of spectrometers; quadrupole, monopole, magnetic sector, double focusing, Wien filter, to mention some [9]. They can be divided into three groups:

- Electric spectrometers
- Magnetic spectrometers
- Combined electric and magnetic spectrometers

If the spectrometry measurements are to be satisfying, the mean free path of the particles must be long compared with the path length [10]. This implies that the vacuum is important. The vacuum level needed depends on the experiment and the geometry of the instrument.

The particles discussed here will be positive ions, but the equations also apply to negative ions and electrons.

#### 2.4.1 Motion of charged particles in electric and magnetic fields

A positive ion with mass $m_i$, charge $z$ and velocity $v$, will be subject to the Coulomb force (equation 2.10) and/or the Lorentz force (equation 2.11) when it enters an electric and/or magnetic field. If the fields are perpendicular to the ion trajectory, they will cause the positively charged ion to bend in a
circular path with the radius \( r \). The bending radius is calculated using that the force(s), acting on the particle, and the centripetal force (equation 2.12), corresponding to the situation, are equal.

\[ F_C = ze \cdot \vec{E} \]  
\[ F_L = ze \cdot \vec{v} \times \vec{B} \]  
\[ F_{ce} = \frac{m_i (\vec{v} \cdot \vec{v})}{r} \cdot \vec{r} \]  

The dislocation of the particle is easily obtained if the bending angle \( \gamma \) is supposed to be small (see Figure 2.4-1) [10]. For an electric field, equations 2.10 and 2.12 and this assumption gives:

\[ ze \cdot E = \frac{m_i v^2}{r} \]  
\[ \sin \gamma = \gamma = \frac{l}{r} \]  
\[ d = \gamma L = \frac{l \cdot L}{r} = \frac{l \cdot L ze \cdot E}{m_i v^2} \]  

And for a magnetic field the corresponding expression for the dislocation becomes:

\[ d = l \cdot L \frac{ze \cdot B}{m_i v} \]  

The distances \( l, L, d, r \) and angle \( \gamma \) are shown in Figure 2.4-1.

![Figure 2.4-1: The trajectory of a positive ion in an electric field. The bending angle is assumed to be small.](image)

If the electric and the magnetic fields are parallel to each other (perpendicular to the ion trajectory), they will cause displacements that are perpendicular to each other. On the other hand, if the fields are perpendicular, the displacements will be parallel and with a correct choice of field strengths (distances identical) they can be made to cancel each other. Then we will have:

\[ ze \cdot vB = ze \cdot E \Rightarrow v = \frac{E}{B} \]  

To obtain the \( m/z \) ratio, it is easiest to use only one field. That will give:

\[ \frac{m_i}{ze} = \frac{v^2}{l \cdot L} \frac{d_e}{E} = \frac{v}{l \cdot L} \frac{d_B}{B} \]  

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2.4.2 Time-of-flight spectrum

A popular method to diagnose ions that are accelerated (or created) at the same instant is the Time-of-flight (TOF) method. This method uses the velocity difference that occur when ions with equal energy per charge have different mass to charge ratios.

The kinetic energy per charge of an ion with mass $m_i$, velocity $v$ and charge $z$ is:

$$ V_z = \frac{m_i v^2}{2ze} \tag{2.12} $$

The time it takes to move a distance $L$ is then given by:

$$ t = \sqrt{\frac{m_i}{2zeV_z}} \cdot L \tag{2.13} $$

If $V_z$ is constant, then ions with different $m_i/z$ will arrive to the detector at different times, creating a TOF-spectrum. Now the remaining problem is to obtain the "equal energy per charge". This can be done in two ways:

- An electrostatic analyser, used to distinguish all ions with one set energy per charge.
- Acceleration of the ions, so all ions have (approximately) the same $V_w$, which is the equivalent acceleration voltage.

The first method can provide a full energy and momentum distribution of the ions, if a scan of all energy per charge is done.

In the second method, the ions are accelerated in an axial electric field, with a potential difference $U$. The ions will then gain energy depending on what charge they have, according to the Coulomb force (equation 2.10) and the simple relation $E = F \cdot l$. The energy gained will be:

$$ E_{\text{gained}} = F \cdot l = ze \cdot U = \frac{m_i (v_f^2 - v_0^2)}{2} \tag{2.14} $$

($v_f$ is the final velocity and $v_0$ the initial). If $v_f >> v_0$, then all ions have almost the same kinetic energy per charge. This demands that the spatial and velocity distribution of the ions in the source and during acceleration can be ignored [8].

2.4.3 Electrostatic analyser

The electrostatic analyser (ESA) consists in principal of two coaxial metallic cylinders with radii $R_1$ (inner plate) and $R_2$ (outer plate) as shown in Figure 2.4-2. The two plates are held at potentials $V_1$ and $V_2$, respectively and have a deflection angle $\Psi$. The radial electric field inside the deflection system is given by:

$$ E_r = \frac{(V_2 - V_1)}{r \cdot \ln \frac{R_2}{R_1}} \tag{2.15} $$

where $r$ is the radius of an equipotential surface and $R_1 \leq r \leq R_2$. In most cases of symmetric polarisation, $V_2 = -V_1 = U/2$, the equipotential surface $V_0 = 0$ exists for [11]:
\[ r = R_0 = \sqrt{R_1 R_2} \equiv \frac{R_1 + R_2}{2} \]  \hspace{1cm} (2.16)

A particle, with the charge \( z \), mass \( m \), and velocity \( v \), incident to the analyser, will follow this circular path and be analysed, only if the following condition is fulfilled:

\[ \frac{m v^2}{R_0} = e z \cdot E_r \left( R_0 \right) \]  \hspace{1cm} (2.17)

which follows from the discussion in section 2.6.1. This can also be written as:

\[ \frac{E_p}{z} = \frac{e R_0 E_r \left( R_0 \right)}{2} = \frac{e U}{2 \ln \frac{R_2}{R_1}} \]  \hspace{1cm} (2.18)

where \( E_p \) is the (kinetic) energy of the particle. Here it is easy to see, that for a given potential \( U \) over the analyser, a certain energy per charge will be analysed. By changing the potential in small steps, from a low value to a high, a complete energy spectrum can be obtained. This requires many measurements if the energy spread is large in the particle beam analysed.

![Diagram](image)

**Figure 2.4-2:** Schematic drawing of an ESA. \( R_1, R_2, R_0 \) are the inner, outer and mean radius of the deflection plates, respectively. \( V_1 = -V_2 = U/2 \) are the potentials of the deflection plates. \( b_{in} \) and \( b_{out} \) are the widths of the input and output slits. \( \psi \) deflection angle of the deflection plates and WEM is a Windowless Electron multiplier used for detection.

### 2.4.4 Magnetic analyser

In this kind of analyser, a magnetic field is used to filter particles with different momentum per charge. It functions the same way as an ESA, but instead of two coaxial cylinders creating an electrical field, there is a strong magnetic field influencing the charged particles. Due to the Lorentz force (equation 2.11) from the magnetic field, the particles with momentum \( P \) and charge \( z \) will move in a circular trajectory with a radius \( r \) according to:

\[ \frac{P}{z} = \frac{m v}{z} = \frac{1}{r e \cdot B} \]  \hspace{1cm} (2.19)
Particles with different momentum can be analysed either by moving the detector or changing the magnetic field.

2.5 Electrostatic probes

To obtain information about the plasma and accelerated beam, electrostatic probes, i.e. charge collectors, are often used. They provide simple measurement arrangements and can be used both close to the target (in the hot area) and at long distances from the target. However, quantitative results obtained with electrostatic probes are often questioned due to the influence of secondary electron emission [11].

2.5.1 Faraday cup

The Faraday cup (FC) is used to measure the intensity, or current, in a particle beam. A beam of positively charged ions falls on a grounded metal plate and causes a current in the electrical wire. This current is measured over a resistance $R$ with voltage amplifiers of very high input impedance.

![Figure 2.5-1: The principle of a Faraday cup.](image)

If the FC only consists of a plain metal plate, it will be very sensitive to secondary electron emission. The signal will be falsely larger due to electrons leaving the plate when the positive ions impinge. It will also be impossible to measure the ion current in a plasma, since the contributions of positive and negative charges will be equal. This can be remedied by placing the metal plate in a metal cup, and put a biased (negative) grid in front of it (Figure 2.5-1). The plasma electrons are then hindered to reach the metal plate, while the ions will have no difficulties at all. The secondary electrons will still be emitted from the metal plate, but they cannot escape from the cup. Instead they have to return to the metal plate, and this way no extra charges are transferred. The signal recorded will originate from the ions only.

The current from a FC with a biased grid will be:

$$I = e \phi S \cdot \sum_{j=0}^{\text{ion}} z_j(t) \cdot n_j(t)$$

where $e$ is elementary charge, $\phi$ is transparency of entrance grid, $v$ is the plasma velocity, $S$ is the area of the collector, $z_j$ and $n_j$ is the charge state and amount of the $j$th ion species ($j = 0$ corresponds to neutral particles).

2.5.2 Ring ion collector

The ring ion collector (RIC) functions as a Faraday cup, with the difference that it is not completely destructive. As the name implies, the collector is a ring with an aperture in the centre. When the ion collector is mounted in the path of a particle beam, the central part of the beam will pass through the collector, but the outer part will be collected, see Figure 2.5-2. To receive a true ion current signal, it is
important that the beam is approximately homogenous. Thus, the collector should not be used too close to the origin of the beam. The biasing of the collector should not be too high, since that would cause significant deflection of the plasma.

![Diagram of a ring ion collector](image)

*Figure 2.5-2: Side view and frontview of a ring ion collector, situated in a drift tube for an ion plasma. Here \( \Phi \) is the diameter of the hole in the RIC.*

### 2.5.3 Micro Channel Plate

The Micro Channel Plate (MCP), or multi channel plate as it is also called, was initially developed as an image intensifier in the 1960s. It consists of two important parts, the channel plate and a phosphor screen, shown in Figure 2.5-3.

![Diagram of a Micro Channel Plate](image)

*Figure 2.5-3: The principal parts of a Micro Channel Plate. \( U_1 < U_2 < U_3 \). The difference between potential \( U_1 \) and \( U_2 \) decides the gain of the MCP, and should be around 1000 V.*

The channel plate is a disc made of optical fibres, glass tubes, with a diameter of between 5 and 20\( \mu \)m. These tubes sit at an angle of 5° to 10° from the normal to the disc. A metal coating is deposited on the front and back surfaces of the glass wafer, and the electrical resistance between the surfaces is about \( 10^7 - 10^8 \Omega \) [8]. If a potential difference is applied over the channel plate there will be an electric field in the channels, and they will function as electron multipliers.

An incoming particle or photon collide with the wall of a glass tube and causes an initial emission of secondary ions. These electrons are accelerated towards the phosphor screen (or the positively biased end of the tube), due to the potential difference. On their way, the secondary electrons will collide with the walls again, and additional secondary electrons will be emitted. This way an avalanche of electrons are created, which finally impinge on the phosphor screen (or is collected). If the electron
avalanche is collected, the signal can be recorded with a time-resolved device, for example an oscilloscope.

The gain of the SEM depends of course on what material is used in the tubes and the accelerating potential difference. But the gain also depends on the charge-state and energy of the impinging particle as well as the incoming angle [14]. This will not be further discussed here but it should be noted that the effect (gain) is, in most cases, not completely linear. However, linearity has been assumed for the range of charge-states and energies discussed in this thesis.

To obtain this electron avalanche, the potential difference over the plate must be at least ~ 300 V and the best result is at 1000V. Then the gain is about 10^4. If the potential difference is set too high, there will be a discharge in the channels and the whole plate is likely to break down. A higher gain can instead be achieved by placing two or more channel plates after each other [8].

An image of the particles impinging on the MCP is obtained by accelerating the electrons, exiting the channel plate, to a phosphor screen. The phosphor transform the energy of the electrons into light [15] and the image can be recorded with a CCD camera.

Since the MCP only function when a potential difference is applied, it can be pulsed to analyse only a part of a particle beam [9]. The pulsing must be done carefully, because a spike in the applied voltage can destroy the channel plate. With a capacitor in series with the channel plate a fast rise time of the voltage is avoided, but on the other hand this makes the gating inexact. The exact gain of the MCP is also a function of the time history of the applied voltage (typically over a few milliseconds before the detection). For short gating pulses and particle pulses, the gain can vary in time.

If the channel plate is hit by too many particles, the exposed part will become saturated and stop function linearly. The particles impinging on the MCP causes the negative charges to move to the positively biased end of the channels. If there are a sufficient number of collisions at a high frequency, there will in the end be no more negative charges to move, and the following impinging particles will not be registered.
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Chapter 3

CERN Laser Ion Source

In this chapter, the CERN Laser Ion Source (LIS) is presented. This is a short presentation how the LIS is built and how it works to give an understanding about the environment the experiments were performed in. It is explained what kind of ions the source can provide and what experiments are done to characterise the source, to give a background of why the diagnostic tools are needed. Moreover, the CO₂-laser and the Master Oscillator - Power Amplifier scheme are presented. More information about the source is found in references [3]-[5], [12], [13] and [16-20].

3.1 Construction

CERN LIS can be divided in three parts; laser, beam extraction and Low Energy Beam Transport (LEBT). After the LEBT a Radio Frequency Quadrupole (RFQ) will be used to pre-accelerate the beam before it is passed on to a linear accelerator when (and if) the source is put into service. It is therefore important to take the transmission to the RFQ into account too. Figure 3.1-1 shows the general layout of the laser ion source experiments at CERN.

![Diagram of laser ion source](image)

**Figure 3.1-1: Plan of the CERN Laser Ion Source. The laser is approximately 30 meters away from the target to avoid parasitic oscillations. The profile harp can be used to measure the beam profile (position and width) and the beam transformer measures the current.**

3.2 CO₂-laser

The CO₂-laser is a Lumonics TEA-601A of the Transverse Excitation Atmospheric (TEA) type (discussed in section 2.1.1), configured in an unstable confocal cavity arrangement. This means that it is a free running laser and several longitudinal modes oscillate at the same time in the cavity. It can generate a light pulse with an energy of 50 J, but when optimised for a high peak power the energy is decreased to 30 J. The wavelength is 10.6 μm (infrared) and the power density on the target (after focusing with a 300 mm focal length parabolic mirror) is approximately 5·10¹² W/cm². The repetition rate of the laser is one shot in 20 seconds. This relatively low repetition rate (1 Hz is required in final version for LHC) is primarily limited by the re-charge time for the main discharge capacitors.
The laser pulse, shown in Figure 3.2-1, consists of a fast initial peak (FWHM 70 ns) followed by a long "tail" lasting up to 1 μs. Approximately 60% of the total laser energy is contained in the initial peak, and the rest in the tail. The low power density tail only produces low charge-states and causes evaporation of the target surface material.

When the laser beam hits the target and produces the plasma, it starts to be reflected by the same plasma. To avoid parasitic oscillations, i.e. coupling between the light reflected from the plasma and the laser cavity, the laser beam is guided with mirrors through a 30 meter long air tube. Without this path prolongation the energy in the initial spike would decrease noticeably. Unfortunately the parasitic oscillations is not completely avoided due to the long time-scale dynamics of the pulse tail.

As the amplitude of each longitudinal mode that oscillates in the laser cavity differs from shot to shot, the time structure of the laser pulse is very unstable. The beating of the different modes produces a characteristic spiked laser pulse (see Figure 3.2-1), with an inter-peak time equal to the round trip of the laser cavity (1.8 m, 6 ns). As a consequence the intensity of the laser beam is always higher or lower than the intensity calculated with the formula:

\[ I = \frac{E}{S \cdot dt} \]  

(3.1)

where \( E \) = energy, \( S \) = surface spot and \( dt \) = laser pulse duration [21]. According to simulations performed at ITEP (Moscow) and TRINITI (Troitsk) [13] the production of the laser plasma is very sensitive to such intensity fluctuations.

This laser is being replaced with a Master Oscillator - Power Amplifier scheme (see section 3.5) but the Lomonics was used for the TIS experiments.

![Figure 3.2-1: Pulse shape from the Lomonics. The initial peak contains about 60% of the energy and the low energy tail the rest.](image)

### 3.3 Target chamber and beam extraction

The chamber containing the target is connected to a variable high-voltage power supply (max. 100 kV) and is isolated from the main vacuum chamber by a ceramic insulator. These chambers are pumped to a vacuum of ~ 5 \( \times \) 10\(^{-7} \) mbar with an ion pump pre-pumped with a turbo pump.

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Chapter 3 CERN Laser Ion Source

The laser beam enters the target chamber through a NaCl window and is focused back onto the target by a copper parabolic mirror with a focal length of 30 cm, see Figure 3.3-1. The target is in form of a short cylinder and it can be rotated from outside the target chamber in order to give a fresh target spot. It is generally lead or tantalum that is used for the experiments. Tantalum has a similar mass to lead and has the advantage of a much higher melting point, which results in less target material being sputtered onto the focusing mirror. Tantalum also has the advantage of isotopic purity, which makes it easier to interpret the results.

The plasma is formed on the target surface and expands through a 30 mm hole in the copper mirror into the expansion chamber. Here the plasma can expand without disturbing external fields since the chamber is connected to the target chamber and thereby held at the same high positive potential. To obtain a flexibility in the system, the expansion chamber consists of a series of telescopic drift tubes which are supported with isolated holders.

At the end of the expansion chamber the ions are separated from the electrons and an ion beam is accelerated through the extraction system. The extraction system consists of two electrode apertures, where the first is held at -10 kV and the second at ground potential. Both applied voltages are capacitively backed in order to remain at their nominal values during extraction of the beam.

![Figure 3.3-1: Schematic diagram of the plasma production and ion extraction.](image)

The apertures can be changed between 20, 25 and 30 mm in diameter and the aperture in the expansion chamber is always the same as in the extraction system. A golden rule in beam extraction is to have the same distance between the expansion chamber and the first electrode as the diameter of the aperture [A].

3.4 Low Energy Beam Transport

When the ion beam leaves the extraction system and enters the Low Energy Beam Transport (LEBT) line it contains a large variety of charge-states. Since all particles are positively charged, there will be a large space charge field and the ion beam will diverge. To first collimate the beam and then focus the wanted charge-states into a Radio Frequency Quadrupole\(^3\) (RFQ), the LEBT contains two pulsed solenoids. The inner diameter of the coils are 120 mm and the solenoids can provide a peak field of 1.4 Tesla on the axis. The vacuum chamber tube going through the solenoids have a diameter of 100 mm.

\(^3\) An RFQ consists of four rods with potentials equal in pairs. By changing the potentials with radio frequency, the injected particles with correct charge to mass ratios are accelerated.
In addition to the solenoids, diagnostic equipment can be installed. There are:

- Faraday cup with 30, 15 and 6.5 mm input apertures
- beam current transformers
- phosphor screen and CCD camera
- profile harp to measure the beam profile

The two solenoids are tuned both in position and magnetic field, to match the wanted ion beam emittance to the RFQ. This tuning is a slow process requiring many shots and to have a rough idea of the ultimate positions and field strengths, simulations are performed. Ideal solenoids, linear space-charge and one charge-state are used in these simulations. The beam is represented by macro-particles ($10^4$ particles) and the trajectory is integrated through the magnetic fields of the solenoids [B].

When this first positioning is done it is possible to perform more complex simulations that incorporates measured fields of the solenoid, two dimensional space-charge calculations and many charge-states ($10^4$ particles per beam). With this simulation it is easy to obtain the emittance in each step and therefore the emittance growth due to solenoid imperfection and non linear space-charge effects.

All the charge-states have different longitudinal focal positions, so in the end there will only be a few charge-states that are accepted and accelerated by the RFQ. Ideally it should be only one charge-state in order to minimise the space-charge effects.

The RFQ used by the LIS-team at CERN is designed to accelerate ions with charge to mass ratios higher than 0.0865 (applicable for tantalum ions with charge-states higher than 16+), with up to 60 mA of a mixture of charge-states. It operates at a frequency of 101 MHz and accelerate ions from 9.6 to 250 keV/u. The input emittance acceptance is 300 mm.mrad.

### 3.5 Master Oscillator - Power Amplifier scheme

With a Master Oscillator (MO) - Power Amplifier (PA) scheme many of the problems of the free running CO₂-laser are solved. With the MO-PA we have:

- Single longitudinal mode, meaning a smooth laser pulse.
- Single transversal mode, which gives a gaussian beam profile and small spot size.
- No low energy tail, which takes 40% of the energy and damages the target.

The MO is designed to produce a stable 100 mJ pulse with a repetition rate of 3 Hz. It can be tuned to produce single, two and multi-mode pulses. Figure 3.5-1 shows the different modes when they are detected with a photon drag detector. When the pulse is coupled into the PA, it will be amplified but the shape of the pulse will remain the same.
Figure 3.5-1: The MO can be tuned to produce single, two and multi-mode pulses. These are measured with a photon-drag detector.

To increase the MO laser power to a useful value for high charge-state generation, the original laser (Lumonics) was converted to a three pass amplifier, Lumonics Power Amplifier (LumonicsPA). In this configuration a 6 J, 6 cm diameter beam is produced with a power density calculated to be $2 \times 10^{12}$ W/cm². The important quantities for the two laser systems are compared in Table 3.5-1. With this much lower power density at the target, it is not possible to obtain the same high charge-states as with the Lumonics.

<table>
<thead>
<tr>
<th>Energy</th>
<th>Pulse length</th>
<th>Shape</th>
<th>Target PD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumonics</td>
<td>29 J</td>
<td>70 ns</td>
<td>Spiked</td>
</tr>
<tr>
<td>MO-LumonicsPA</td>
<td>6 J</td>
<td>65 ns</td>
<td>Smooth/Spiked</td>
</tr>
</tbody>
</table>

Table 3.5-1: The important quantities for the Lumonics and the MO-LumonicsPA.

All instruments need to be tuned to perform its best, and the Master Oscillator is no exception. To control the stability and noise level of the pulse from the MO, a program in LabView⁴ was written to measure the MO pulse amplitude, width and smoothness. A closer explanation how the program works is given in Appendix C, and the evolution of the pulse stability is shown in Figure 3.5-2.

Figure 3.5-2: Statistical record of the number of good and bad shots. The shots are counted as good if the h ave less than 10% noise. The MO operates at 3Hzs and the program runs at 1 Hz which means that approximately every third shot is recorded and contributes to the statistics. Percent values shown in MO performance 2 May 97, are the percentage bad shots in that interval.

⁴ LabView is a programming language using graphic code. It is developed to give an easy way of control and acquire data from laboratory instruments.
The program runs at approximately 1 Hz and the MO at 3 Hz, which means that only every third pulse contribute to the statistics and 3600 shots are recorded in one hour.

3.6 Charge-state distributions

The charge-state distributions (CSD) are normally measured using an electrostatic analyser (ESA) or a magnetic spectrometer together with a time resolved detector, typically a Secondary Electron Multiplier (SEM) tube. This gives a time-of-flight (TOF) spectrum where the individual charge-states can be observed. See Figure 3.6-1.

To obtain a complete charge-state distribution 50 - 100 shots have to be made at different ESA settings, and the TOF spectrum recorded for each shot. The spectra are evaluated to achieve the relative abundance for each charge-state. These current values can be normalised with the current for the whole beam, often measured with a Faraday cup. The current values are summed for each charge-state to give the CSD.

![Figure 3.6-1: Time-of-flight spectrum for tantalum measured with an ESA together with a SEM at a distance 3 m from the target.]

With the MO-LumonicsPA it is possible to see what effect the pulse shape has on the CSD. The CSDs shown in Figure 3.6-2 have been measured 3m from the target using the free-running laser (30 J) and the 6 J MO-LumonicsPA scheme with single-mode and multi-mode pulses. The currents indicated are based on a normalisation with a current signal measured with a Faraday cup 4 cm after the final extraction electrode.

![Figure 3.6-2: Left - CSD for Lumonics, Right - CSD for MO-LumonicsPA performing in single-mode (SM) and multi-mode (MM). Observe the different scales of the diagrams.]

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3.7 Emittance measurements

The charge-states of interest are only present for a few µs during the first spike of the extracted ion pulse. Thus, to measure the emittance (explained in Appendix D), it is necessary to use a device that can be active for that specific part of the beam only. It is also convenient to be able to perform the measurement during one shot to avoid shot-to-shot instabilities.

The emittance of the LIS beam is measured using the “pepper-pot” technique. The set-up is shown in Figure 3.7-1. A perforated metal foil, or pepper-pot, is placed on the axis of the ion beam. It consists of a 2 mm square array of 80 µm diameter holes. The ions pass through the holes and impinge on a microchannel plate (MCP) after some drift length. A phosphor screen after the MCP turns the spatial pattern of the arriving beamlets into a light pattern that is recorded with a CCD camera. This method was recently modified and now the MCP has been replaced with a phosphor screen.

The transverse velocity distribution of the beam can be calculated using the size of the image each beamlet produces. The angular position of the images is calculated from the geometry of the system. From this information of the whole beam it is possible to plot a phase space ellipse and calculate the transverse beam emittance.

![Diagram](image-url)

*Figure 3.7-1: Emittance measurement using a pepper-pot screen. \( d_1 = 15 \text{ mm}, d_2 = 15 \text{ mm}, d_3 = 25 \text{ mm}, d_4 = 145 \text{ mm}, \) aperture of extraction system = 7.5 mm.*
Chapter 4

Thomson parabola Ion Spectrometer

In this chapter the instrument, its functionality and installation are described. It also includes the experiments that were performed with it and which quantities were analysed.

4.1 TIS operation

The Thomson parabola ion spectrometer (TIS) uses both an electric and a magnetic field together with a 2D spatial detector to resolve the energy per charge ($E/z$) and momentum per charge ($P/z$) of the incoming ions. The two fields are parallel and bend the trajectories of the ions in directions perpendicular to each other. The solution of the equations of motion for a charged particle through the fields show that all particles with equal charge to mass ratio will follow a parabola. This results in an image of parabolas, where each parabola corresponds to one mass per charge ratio ($m/z$) and a full energy and charge-state distribution can be measured in one shot.

4.1.1 Construction

The TIS consists in principal of a system of two diaphragms, which forms the ion beam or plasma object, a deflection chamber with electric and magnetic field and a registration system (Figure 4.1-1) [22].

The fields are parallel to each other, perpendicular to the ion beam and are arranged in series with the magnetic field first. Separation of the electric and magnetic fields gives the possibility of maximising the length to gap ratio in the magnet and with that minimising the influence of stray and fringing fields on the measurements. Additionally the magnet-pole edge profiles are tapered so the effective field boundary is very nearly the same as the physical pole edge. These and the deflecting condenser plates are specially profiled to ensure that all ions have the same path length in the deflecting fields [11]. See Figure 4.1-2.

![Diagram of Thomson parabola ion spectrometer](image)

Figure 4.1-1; Principle parts of the Thomson parabola ion spectrometer. 1- the first diaphragm, 2- second diaphragm, 3- magnet coil, 4- pole shafts of magnet, 5- deflecting condenser plates.
Figure 4.1-2: Ion trajectory in TIS. The magnet-pole edge profiles and deflecting condenser plates are shaped to give all ions equal path length. \( L_s = L_e = 80 \text{ mm}, L = 305 \text{ mm}, l = 10 \text{ mm}, d_b = 5 \text{ mm} \) and \( d_E = 20 \text{ mm} \).

To measure the ion current entering the mass spectrometer, a ring ion collector is situated in the beam pipe before the TIS. The ion collector captures the ions in the outer part of the beam, and lets the central part pass undisturbed (section 2.5.2).

### 4.1.2 Parabolas

From the solution of the motion equation of a charged particle entering the two parallel fields \( \mathbf{E} \) and \( \mathbf{B} \) (section 2.5.1), the coordinates in the detection plane will be:

\[
x = \frac{\alpha z e U}{E_i} \tag{4.1}
\]

\[
y = \frac{\beta z e B}{\sqrt{m_i E_i}} \tag{4.2}
\]

After eliminating \( E_i \), the (kinetic) ion energy \( (m_i v^2/2) \), we have:

\[
x = \frac{\alpha m_i U}{\beta' e z B^2} \cdot y^2 \tag{4.3}
\]

where \( U \) is the potential difference between the electrostatic deflecting plates, \( z \) the ion charge, \( m_i \) the ion mass and

\[
\alpha = \frac{(L + L_E/2)L_E}{2d_E} \tag{4.4}
\]

\[
\beta = \frac{(L + L_B + l + L_B/2)L_B}{\sqrt{2}} \tag{4.5}
\]

The distances \( L_E, L_B, l, \) and \( d_E \) are shown in Figure 4.1-2.

This equation gives, for fixed \( U \) and \( B \) one parabola for each \( m_i/z \) ratio, along which all ions should lie. The position along the parabola gives the ion energy and momentum. Heavier and more energetic ions
will be located closer to the origin of the parabola while lighter and less energetic will be further out. Figure 4.1-3 illustrates the geometry of the particle distribution after the TIS.

A horizontal line, fixed \( x \), gives all points with the same \( E_i/z \) ratio:

\[
\frac{E_i}{z} = \frac{\alpha e U}{x} \tag{4.6}
\]

Conversely, points on the same vertical line, fixed \( y \), have all the same \( P_i/z \) ratio:

\[
\frac{P_i}{z} = \frac{\sqrt{2} \beta e B}{y} \tag{4.7}
\]

All the points with the same velocity lie on a line:

\[
v = \sqrt{2} \frac{\alpha}{\beta} \frac{U}{B} \frac{y}{x} \tag{4.8}
\]

with the required gradient, from the origin of the coordinates, 0xy.

Figure 4.1-3: Parabolas from TIS. The boxes give the positions for all ions with one specific \( E_i/z \), the ellipses all ions with one specific \( P_i/z \) and the stars all ions with one specific velocity.

### 4.2 Installation

To be able to correctly evaluate the data obtained, the alignment of the Thomson parabola spectrometer is very important. A collimated beam is necessary to get the right conditions for the spectrometer and it is obtained by centring the diaphragms. It is also crucial that the electric and magnetic fields are accurately calibrated.
4.2.1 Setting up the TIS

During two weeks in May 97, a small group from Prague and Warsaw\(^1\) came to CERN with their TIS. Thanks to intensive exchange of information preceding the visit, the TIS could be adopted to the existing experimental set-up within a few days. The final set-up is shown in Figure 4.2-1.

A second pump group was connected to the TIS to be able to get a good vacuum faster. This also made it possible to open either the target chamber or the TIS without interfering with the other. Nevertheless there were some problems to get a satisfactory vacuum. Only \(10^{-2}\) mbar was initially obtained where \(2 \cdot 10^{-5}\) mbar is required [C]. After leak detection we found large leaks in the TIS bellows, welding joints on the deflection chamber, gate valve, bellows to the pump and on a feed-through flange. Most of these leaks were repaired and the pump was moved closer to the TIS to make the pumping more efficient. After this we obtained a vacuum around \(7 \cdot 10^{-4}\) mbar.

![Diagram of TIS setup]

*Figure 4.2-1, The final set-up of the TIS and LIS.*

4.2.2 Alignment

A HeNe-laser was used to align the set-up. The laser was fixed in a holder that could move in the horizontal plane and was placed in the same position as the detection plate. Since the final image consists of parabolas, the central spot must be in a corner of the detection plate. Consequently, the laser beam was aimed from the upper right corner of the detection plate, through the Thomson spectrometer and the two diaphragms to the target. This was done in three steps.

*Step one.* The second diaphragm, with a diameter of 0.10 mm, was removed and the laser was adjusted to let the beam through a corner of the deflection chamber and the first diaphragm, with a diameter of 1.0 mm. The path of the laser beam was controlled with a piece of paper.

*Step two.* The small diaphragm was put back and by moving both the diaphragm and the laser in very small steps, the laser beam was made to go through both apertures. The Thomson spectrometer was internally aligned and the remaining work was to align it to the target.

*Step three.* By moving the TIS, or rather the plate it is fixed on, the laser beam was directed through the centre of the extraction hole in the main chamber. Then the point of impact on the target was controlled and the position of the TIS was adjusted to the target.

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4.2.3 Accuracy of magnetic and electric fields

The magnetic field is generated by an electromagnet, and the calibration between current and magnetic field was done with a Hall-probe. This calibration was performed before the CERN experiments and the result was [C]:

\[ B = 0.905 \cdot I[mA] - 45.6 \text{ [Gauss]} \]  \hspace{1cm} (4.9)

From now on the reference will be to the current fed to the magnet instead of the actual magnet field.

The electric field is generated by placing a voltage over two parallel conducting plates. The plates are placed at equal but opposite potentials. With a gap of 20 mm between the plates, E-fields up to 1 kV/cm are easily achieved.

4.2.4 Detection

After the alignment was completed, the HeNe-laser was replaced with a Multi Channel Plate (MCP) coupled with a phosphor screen. The ions impinged on the MCP and the resulting light distribution was recorded with a CCD camera. For the first days of experiments a Tektronix Video camera C1002 was used. This was later replaced with a Hadland Photonics Image intensified CCD camera, which can be gated with 50 ns resolution.

Pulse shapes from the laser and the ion collector were also recorded. The laser pulse was detected with a CdHgTeZn crystal with response time < 1ns.

4.2.5 Software

The images from the camera were analysed using two computer programs. Since the actual fields sometimes differs from the applied fields, due to miscalibration or instrumental errors, it is necessary to include a field correction. The field correction can be calculated using calibration of low charge-states parabolas, which are usually easily defined. This field correction should then remain constant during one measurement series.

Prague program
This program can give diagrams with X[mm] - Y[mm] axis or E/\zeta[keV] - P/\zeta[10^9 u cm/s] axis, in which it is possible to add arbitrary velocity lines and parabolas calculated with the input data. It can also give an intensity profile for a constant E/\zeta. The field correction is the ratio between the intended magnetic field and the magnetic field needed to make the parabolas fit. i.e. when this term is 1, we have no field correction [23].

TP-Imager
To get the intensity profile along a parabola, a second program was written. This was later further developed and finally included most of the features of the Prague program.

This program reads a file from one of the cameras and present it as an image. The parabolas are then calculated using equation 4.3 and:

\[ x = ay^2 + by + c \] \hspace{1cm} (4.10)

This gives the parabolas as:

\[ (x - x_0) = \frac{\alpha m_e}{\beta^2 e \zeta} \cdot \frac{U}{B^2} (y - y_0)^2 \] \hspace{1cm} (4.11)

where \( x_0, y_0 \) is the central spot and therefore origin of the parabola.
By defining the origin and giving the correct values of $U$ and $B$ it is possible to acquire a correct parabola for the wanted charge-state. The matching of calculated parabolas to the measured ones are done by changing the pixel/mm value for $y$. This gives the same correction for the parabolas as the field correction in the Prague program since we have the relation:

$$x \propto \frac{U}{B^2} \cdot y^2 \quad (4.12)$$

The pixel intensities along these parabolas are the intensity profiles. With a complementary program in Excel it is from these intensity profiles possible to attain energy distributions of each charge state and charge-state distributions for each shot. See section 4.3.2.

Velocity lines and intensity profiles for these lines can also be obtained, as well as a full intensity-velocity distribution for all ions registered on the channel plate (irrespective of charge-state). As each point in the image correspond to one velocity, a histogram with constant $\Delta v$ for each bin can be produced from the TIS image. This histogram can be further manipulated in Excel and the result is an intensity-velocity diagram.

The intensity-velocity diagram can be transformed to a intensity-time diagram for a specific distance from the target. This produces an equivalent current-time plot, which can be compared with the ion collector signal.

### 4.3 Experiments with ion plasma

There are many interesting features that are possible to measure with the information obtained from the experiments with the TIS. The analysis was limited to the most relevant quantities. Most of the results attained can be compared with results from measurements with other experimental methods, which is important in order to evaluate the TIS.

#### 4.3.1 Principle operations

A typical image obtained with the TIS is shown in Figure 4.3-1. This image has been processed with TP-imager and it includes calculated parabolas and velocity lines. As seen, the resolution is not very good for high charge-states (>+15) in the plasma case. Figure 4.3-2 shows the corresponding ion collector signal.

The ion collector was placed 1562 mm after the target and with the basic length-time-velocity relation we have the following dependence:

$$t = \frac{1.562}{v} \quad (4.13)$$

where the velocity is given in units of $10^8$ cm/s and the time in $\mu$s.

It is clearly seen which group of ions in the image correspond to which peak in the ion collector signal. The matching of velocities and times in Figure 4.3-1 and Figure 4.3-2 is given in Table 4.3-1. The energies included in the ion collector diagram are kinetic energies for tantalum ions.
Figure 4.3-1: Image from TIS with parabolas and velocity lines in units of $10^8$ cm/s, calculated with TP-imager. The parabolas in the image are for tantalum with charges +1, +2, +15, +20 and +25.

Figure 4.3-2: The ion collector signal corresponding to the image in Figure 4.3-1. It is clearly seen which group of ions corresponds to which peak in the signal. The energies indicated are kinetic energies for tantalum ions, distance from target to measuring point is 1562 mm.

<table>
<thead>
<tr>
<th>Velocity ($10^8$ cm/s)</th>
<th>Time (μs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.04</td>
<td>39.1</td>
</tr>
<tr>
<td>0.09</td>
<td>17.4</td>
</tr>
<tr>
<td>0.15</td>
<td>10.4</td>
</tr>
<tr>
<td>0.53</td>
<td>2.95</td>
</tr>
</tbody>
</table>

Table 4.3-1: Velocities and corresponding times according to equation 4.16.

The limiting factors for the resolution are both the size of the Multi Channel Plate (MCP) and the maximum fields that can be attained in the deflection chamber. In these experiments we used an MCP with a diameter of 10 cm, and the maximum fields were 1.20 A (which gives 0.104 Tesla) for the magnetic field and 2.0 kV for the electric field [11].
4.3.2 Energy distributions

From the intensity profile of a parabola, an energy distribution can be calculated. The intensity profile can be presented as \( dQ/dy \) versus \( y \) (see Figure 4.3-3), where pixel intensities along the defined parabola in the image is taken as \( dQ/dy \) where \( Q \) is the total charge. This is then converted to \( dQ/dE_i \) versus \( E_i/\beta \) by using equation 4.2:

\[
E_i = \frac{\beta^2 \gamma^2 e^2 B^2}{m_i \gamma^2} 
\]

(4.14)

\[
\left| \frac{dQ}{dE_i} \right| = \frac{m_i}{\beta^2 \gamma^2 e^2 B^2} \frac{y^3}{2} \frac{dQ}{dy} 
\]

(4.15)

After this transformation the raw energy distribution can be seen in Figure 4.3-4. The distribution at the higher energies originate from the central spot. The smaller but more intense part at lower energies originate from the ions, along the parabola where the intensity profile was taken. As the intensity of the central spot comes from x-rays and photons from when the laser hits the target, this part must be excluded. The remaining part is shown in Figure 4.3-5.

The camera records the intensity from the phosphor screen, which is activated by the electrons from the MCP. The gain of the MCP is considered to be (approximately) proportional to the charge of the ion impinging on it. Consequently it is the current of the ions that are detected and not the number of ions. Thus this method gives a correct relative picture of the energy-distribution but it must be measured in arbitrary units.

![Figure 4.3-3: Intensity profile of the parabola corresponding to Ta\(^{189}\) in Figure 4.3-1. The high intensity of the central spot reduces the gain possible to set on the camera. The intensity interval is 0-256.](image)

![Figure 4.3-4: Energy distribution calculated from the intensity profile above. The distribution at the high energies originate from the central spot and the smaller but higher intense part at lower energies originate from ions on the parabola. Note that the curve rises immediately after the zero.](image)
Figure 4.3-5: The interesting part of the energy distribution above is between 0 and 25 keV. Integration of this graph gives the relative amount of current from ions with the charge-state +20.

4.3.3 Charge-state distributions

A charge-state distribution (CSD) gives the relative amount of each charge-state in the beam. The abundance of each charge-state, in arbitrary units, can be found from the integration of the corresponding energy distribution. I.e. the CSD of the beam is achieved when the energy distribution of all charge-states in the beam are integrated.

To avoid having contributions from the central spot, the integration area has to be limited. One way to do that is to set a highest \( E/z \). Looking at a camera image this corresponds to cutting away the lower part of the image. An unwanted side effect is that this may also cut wanted ion intensity if the shot had a high energy peak.

Another way to exclude the central spot is to set a highest \( P/z \). This way the wanted intensity from the parabolas of the high charge-states is not affected at all, but for the lower almost everything is cut away.

In most of the images analysed, the lower charge-state ions are either outside the image or difficult to distinguish from the central spot. This and the fact that the high charge-states ions form the interesting part makes of the analysis, makes the later method preferable despite its disadvantages.

The easiest way to obtain this limitation is to set a minimum x-axis pixel for integration. The central spot is almost the same size from shot to shot and can therefore be restrained with a fixed pixel number. \( P/z \), on the other hand, will change for different B-fields and therefore involve more work if it is to be taken as limitation for the integration.

This brings the calculation to be:

\[
\int_{p}^{p_0} \frac{dQ}{dE_i} dp = \sum_{p} \left( \frac{dQ}{dE_i} \right)_p \cdot \left[ \left( \frac{E_i}{z} \right)_p - \left( \frac{E_i}{z} \right)_{p+1} \right]
\]  

(4.16)

where \( p \) is the x-axis pixel number. This will give the relative amount of current in each charge-state.

4.3.4 Velocity and time diagrams from TP-imager

TP-imager can give an intensity - velocity diagram originating from the image (see section 4.2.5). A typical diagram is shown in Figure 4.3-6. For easier comparison with the ion collector signal, the diagram is converted to a intensity-time diagram. This is done using the distance between the target and the ion collector and the two formulas:
\[ t = \frac{1.562}{v} \]  
\[ \frac{dQ}{dt} = v^2 \frac{dQ}{dv} \]  

The result shown in Figure 4.3-7 can be compared with the ion collector signal in Figure 4.3-2. A visual comparison does not say much more than that the peaks are at the same time, but integrating over time in the ion collector signal and the velocity diagram (converting the time to velocity again) for all shots in a series should give a good correlation, which helps to confirm correct calibration of the TIS.

![Intensity - velocity diagram](image)

*Figure 4.3-6: Intensity - velocity diagram for the image shown in Figure 4.3-1, derived with TP-imager.*

![Intensity - time diagram](image)

*Figure 4.3-7: Intensity - time diagram achieved as a transformation of the diagram Figure 4.3-6, as it would be at the position of the ion collector. This is the expected ion collector signal for the shot analysed.*

### 4.4 Experiments with ion beam

This was a new exciting field of experiments, with few earlier results to compare with. Similar experiments with accelerated ions have before this only been done at the Russian institute ITEP. At CERN recombination rates and CSDs have been done using a one dimensional detector [D]. Again the time available did not allow a complete analysis of the data. The main focus has been put on the recombination\(^2\) of the ions.

\(^2\) Recombination is when an ion recombine with an electron and becomes less charged.
4.4.1 Principal operation

A typical image obtained with accelerated ions is shown in Figure 4.4-1. Compared with the plasma case, it is here easier to see where the parabolas should lie. The excellent agreement of the calculated parabolas to the measured gives confidence in the method and the results.

As explained in section 4.2, all ions accelerated with the same voltage should give one horizontal line if there was no recombination. The recombination gives the ion more energy per charge, since there is no energy loss. Consequently the recombined ions are found closer to the origin, on the parabola corresponding to the charge it has when it is detected.

![Image of parabolas and labels](image)

*Figure 4.4-1: Accelerated ions that are not recombined will be distributed along a horizontal line. Recombined ions will be less deflected, since they have more energy per charge when they are detected. They will end closer to the origin of the parabolas.*

4.4.2 Charge-state distribution

To get an approximate CSD, one can take an intensity profile along the unrecombined ions, which lie on the highest horizontal line. The profile for Figure 4.4-1 is shown in Figure 4.4-2. The peaks for the different charge-states are not always this clear, but here it is easy to distinguish the different peaks with some comparison with the image.

![Graph of intensity profile](image)

*Figure 4.4-2: Intensity profile along the unrecombined ions in Figure 4.4-1. The numbers indicates which peak corresponds to which charge-state.*
4.4.3 Recombination along a parabola or velocity line

An intensity profile along a parabola or velocity line is shown in Figure 4.4-3. These profiles are pixel intensity versus pixel number. What is interesting here is how many of the ions are in the main peak, i.e. the number of ions that do not recombine between extraction and detection. The analysis is simply to integrate over the main peak and compare that value with the integration of the whole profile, without the central spot.

The velocity lines follow the track of one ion (ions retain the velocity given by extraction irrespective of any recombination), so the intensity profile will show how many times one charge-state recombined. The parabola on the other hand will show how many groups of ions recombined to that charge-state. If for instance the +15 parabola has 4 defined peaks, it means that +18 to +16 recombined to +15.

![Intensity profile, parabola](Intensity profile, parabola)

![Intensity profile, velocity line](Intensity profile, velocity line)

Figure 4.4-3: Intensity profile along parabola +10 and a velocity line, ending at the uncombined +10 ions, in Figure 4.4-1. Here we have four separated peaks for the parabola and five for the velocity line. This clearly indicates that there were three groups of ions recombining to +10, and the ions extracted as +10 was recombined to +3, +8, +7 and +6.

4.4.4 Recombination from integrating between horizontal lines

For the data obtained with the Hadland Photonics camera, it is possible to use the cameras image processing software to integrate between horizontal lines and subtract the background.

If the lines are chosen correctly, this divides the image in an unrecombined and a recombined part. The integration of these parts results in two traces or intensity profiles. Even though the background is subtracted there remains some noise in the traces. To minimise the effect of this, it is only the area of the big peaks that have been considered to calculate the recombination rate. Figure 4.4-4 shows how the lines were selected and the resulting traces.
Figure 4.4-4: Upper - the image from the TIS is divided into two parts, unrecombined and recombined ions respectively. Middle - the resulting trace or intensity profile from unrecombined ions after subtracting the background. Lower - this is all the intensity from recombined ions with the background subtracted. Even though the background is subtracted in the two traces, there is still some noise left. The recombination rate therefore only consider the areas of the big peaks.
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Chapter 5

Results from ion plasma experiments

A large number of experiments (about 140 saved shots with ion plasma) were performed during the week. It has not been possible to do a thorough analysis of them all. The most thorough analysis has been performed on two series of shots, where the first series has 12 recorded shots and the second 25. These two series were performed in different conditions concerning the applied voltages and current, but they were both done on one target spot each.

This chapter contains all the results obtained from the analysis and the main discussion and the conclusions are presented in chapter 7.

5.1 Conditions and data analysed

In the first series the current applied to the magnet was \( I_M = 300 \text{ mA} \), the voltage over the condenser plates \( V_E = 90 \text{ V} \), voltage to MCP 1.1 and 6.1 kV and the shots analysed were number 1, 3, 5, 6, 8, 10 and 15. The field correction in the Prague program was 0.97 (see section 4.2.5).

In the second series \( I_M = 400 \text{ mA} \), \( V_E = 260 \text{ V} \), with 1.15 and 6.15 kV to the MCP and shots number 1, 3, 5, 6, 8, 10, 12, 14, 16, 18, 20, 21, 23 and 25 were analysed. The field correction used was 0.87.

The names of the data files, in which the data were saved, are found in Appendix A.

5.2 Charge-state distributions

Charge-state distributions (CSDs) for the shots in the first series show charge-states 15 to 27 (see Figure 5.2-1). The second series' of analysed shots have CSDs show charge-states 16 to 27 (see Figure 5.2-2). Separate CSD for all shots are found in Appendix A. Because of the uncertainties that the calculated parabolas coincide with the measured ion parabolas, it is not wise to compare shots or distributions from different series.

From the information in the first series, we can see that the CSD does not change drastically with number of shots on the same target spot. There is a small tendency that the intensity of charge-states 25 to 27 decreases. This indicates that the focus on the target is good enough for the laser to produce high charge-state ions for at least 15 shots.

For the second series, the large variation in the CSDs between the shots makes it difficult to draw any similar conclusions. The possible reasons for these disparities are discussed in section 7.1.2.
Chapter 5 Results from ion plasma experiments

Figure 5.2-1: All CSDs for the first series in one graph. The CSD does not differ much from shot to shot, which indicates that the focus on the target is within the limits to get high charge-states ions for the first 15 shots.

Figure 5.2-2: All CSDs from series two in one graph. The big variation between them is discussed in section 7.1.2.

In series one the peak stay quite stable to charge-state 22, but in series two there is a large variation with the mean peak charge-state 23 (see Figure 5.2-3). In normal operation it is important to know how the intensity of one charge-state varies from shot-to-shot. This is shown in Figure 5.2-4 for the two series.

Figure 5.2-3: Peak charge-state variation for the two different series.
5.3 Energy distributions

An example of energy distribution for charge-state 22 in the first series is shown in Figure 5.3-5, and for charge-state 23 in the second series in Figure 5.3-6. All energy distributions are found in Appendix A.

For the first series the peak intensity lies around 3 keV per charge, but for the second series it is around 6.5 keV per charge. The only deliberate difference between the two series are the applied fields in the deflection chamber.

This difference in peak energy per charge can be explained by two things, the sensitivity of the camera used and the uncertainty the high field correction means. See section 7.1.2.

Figure 5.3-5; Energy distributions for charge-state 22 for shot number three in the first series.

Figure 5.3-6; Energy distributions for charge-state 23 for shot number three in the second series.
5.4 Comparison ion current and arrival of high charge-states

A velocity diagram from TP-imager transformed to a time diagram, as explained in section 4.3.4, will give an expected appearance of the ion collector signal. Some ions are lost outside the phosphor screen, especially low charge-states, so the resulting plot is not complete. For the time when the high charge-states arrive, there should be a good correlation.

The time when the high charge-states arrive to the ion collector is calculated from velocity lines in the TP image. For the first series it is 3 - 8μs and for the second 3 - 5μs. These times are indicated in the ion collector signals with vertical bars. The time difference when the high charge-state ions arrive in the two series, is probably an effect of the sensitivity of the camera or the uncertainty in the high field correction indicates, see section 7.1.3.

The ion collector signals and corresponding intensity-time diagrams for one shot in the first series is shown in Figure 5.4-7 and for the second series in Figure 5.4-8. Diagrams for all shots are shown in Appendix A. The correlation between these signals/diagrams are shown in Figure 5.4-9, where the bars are the integral in the ion collector signal and the line is the integral in the velocity diagram for the same time. The integral of the IC signal is proportional to the charge collected. Since the signals always are presented in volts and not transformed into current, the unit of the Y-axis is μVs.

---

Figure 5.4-7: Ion collector signal and time diagram from TP-imager for the third shot in the first series. They have both μs as the unit of the x-axis. The ion collector diagrams have measured volts on the y-axis while the time diagram have dQ/dt in arbitrary units.
Figure 5.4-8: Ion collector signal and time diagram from TP-imager for the third shot in the second series. The axis are the same as in Figure 5.4-7.

Figure 5.4-9: Correlation between the integrated value of ions arriving between certain points in time, using the ion collector signal and the TIS image. For the first series the high charge states arrive to the IC 3-8 μs after leaving the target and for the second series the same time is 3-5 μs. The difference can be studied in the TP diagrams in Figure 5.4-7 and Figure 5.4-8.
(Readers own notes)
Chapter 6

Results from ion beam experiments

The main focus has been put on the recombination of ions. This is possible to see in all images with accelerated ions. From the data available we could also choose to see the recombination in time, since we used a gated\textsuperscript{1} camera, and the effect of an attenuated laser beam.

As in chapter 5, this chapter will give all the results obtained and the discussion is found in chapter 7.

6.1 Conditions and data analysed

The gated images were obtained with the Hadland camera. Nine shots were analysed where the first five had a 2 µs time window and the last four 4 µs time window. The current applied to the magnet was 1110 mA, voltage over the condenser plates 2000 V and voltage to the MCP was 0.95 and 5.95 kV. The shots were number 7 to 15 on the same target spot, starting with the earliest time window.

A second set of images analysed were obtained with the Tektronix camera. The current to the magnet was 1110 mA, the voltage over the condenser plates 2000 V and voltage to the MCP was 0.85 and 5.85 kV. First was one shot with a 24J laser beam and second a shot with 13J laser beam, they were shot number 17 and 19 on the same target spot.

The names of the data files for these shots are found in Appendix B.

6.2 Recombination in time using parabolas and velocity lines

From the gated images, the intensity profile along a parabola or velocity line does not have entirely clear peaks. All profiles are found in Appendix B. Two examples are shown in Figure 6.2-1 and Figure 6.2-2, for a parabola and velocity line respectively. A comparison between the images shows approximately where the peaks are located (indicated with arrows or numbers in the diagrams) and it can be stated that the ions recombine 3-4 times.

\textsuperscript{1} With a gated camera, it is possible to record over a small (µs) time window, where the starting and ending times can be set to wanted values.
6.2.1 Along parabolas

Because of the uncertainty of where the main peak starts and ends, we choose two widths for defining it. These are 6 and 11 pixels. The difference in the result is noticeable for the +20 parabola, but for the +15 and +10 parabolas it gives no significant change. The percentage of unreacted ions in the different time windows are shown in Figure 6.2.3. Trend lines included are polynomial of third order. The proportion of the ions, that have undergone one or more recombinations, is the recombination rate, i.e. the recombination is the percentage of the ions that are not recombined. From the diagrams it is seen that the recombination is 55-75%.
6.2.2 Along velocity lines

From an intensity profile along a line of constant velocity, it was easier to distinguish the main peak. For all profiles, the main peak has been taken as 11 pixels. The percentage of unrecombined ions that was extracted as +10, +15 and +20 respectively is shown in Figure 6.2-4. Calculated this way the average recombination is about 70% for +10 and +15 ions and about 80% for +20 ions. The recombination increases with time, suggesting that slower ions are more likely to recombine.

Figure 6.2-4; The recombination of ions increases with time. This suggests that recombined ions lose some velocity. Average recombination is about 80% for +20 ions and 70% for +15 and +10 ions.
6.3 Recombination in time using the entire image

Integration between horizontal lines in the images should be the best way to calculate the recombination rate since it uses the whole image. The images are rotated approximately 6 degrees, which can be adjusted in TP-imager, but not in this third program, the CCD cameras control program (which includes some simple image processing). It is therefore impossible to exactly separate the unrecombined ions from the recombined. This effect is not large but adds some uncertainty to the results, which are shown in Figure 6.3-1. The divisions were always made in favour of the unrecombined ions.

![Percent unrecombined ions, entire image](image)

Figure 6.3-1: Using integration between lines, the recombination rate is about 65%. The images are rotated 6 degrees and the division was made in favour of the unrecombined ions, this is a positive estimation.

6.4 Recombination as function of laser energy

The laser beam was attenuated with a teflon foil, situated between the last mirror and the salt window (see figure 3.1-1). We had only one thickness of the foil, 100 μm, hence we only have two energies to compare. Without teflon foil the energy from the laser is about 24J. With foil it is about 13J. The laser energy was measured with a Balometer.

These images were taken with the Tektronix video camera, so again there is a problem with the threshold sensitivity. All pixels intensities under 24 are cut which means that some peaks might not be seen. Therefore these numbers are not completely reliable. The diagrams in Figure 6.4-1 show how the recombination changes for different parabolas and velocity lines and for the two energies.

Average recombination following a parabola is 54% for the 24J laser beam and 31% for the 13J laser beam. Following a velocity line the average recombination is 61% and 36% respectively. Thus it seems like higher laser energy leads to more recombination. This is further discussed in section 7.2.2.

![Percent unrecombined ions for two laser energies](image)

![Percent unrecombined ions for two laser energies](image)

Figure 6.4-1: Left - Percent unrecombined ions following a parabola. Right - Percent unrecombined ions following a velocity line. With laser energy 13J the recombination is less than with laser energy 24J. These numbers are not entirely reliable, since the camera cuts all pixel intensities under 24.
6.5 CSD in time

As for the intensity profiles along a parabola or velocity line, the intensity profile of the uncombined ions do not have very clear peaks. An example is shown in Figure 6.5-1 and all profiles are found in Appendix B. To distinguish the peaks, it is necessary to compare the profile with the image it originates from. This is not simple, even if there are parabolas included in the image.

A comparison between the different CSDs is even more difficult. To make it more simple we estimated the location and width of all peaks and integrated the intensities. Since the peaks can move from shot-to-shot and some of the peaks are only four pixels in width, this is only an approximate CSDs. Some of the uncertainty is lost if the peaks are grouped into three. These CSDs are shown in Figure 6.5-2.

The CSDs for the different time windows do not change as expected, there are too many high charge-state ions in all the windows. The reason is discussed in section 7.2.

![Intensity profile from uncombined ions in the image where the camera is gated 16-20 μs. The numbering of the peaks are made with a comparison with the image, where parabolas were included.](image)

![Charge-state distributions in time](image)

Figure 6.5-1; Intensity profile from uncombined ions in the image where the camera is gated 16-20 μs. The numbering of the peaks are made with a comparison with the image, where parabolas were included.

Figure 6.5-2; With a gated camera it is possible to get a CSD in time. Notice that the first five shots have a time window of 2 μs and the last four shots have 4 μs time window.
Chapter 6  Results from ion beam experiments

Changing between 2 and 4 µs time window has an effect in the CSD (see section 7.2.4). For the larger time window, the camera has longer time to record the light which, due to the long phosphor decay time, can double the amount of light recorded.

Following the charge-states groups 16-18 and 19-21 it looks like in Figure 6.5-4 and Figure 6.5-3. Here the change of time window is obvious, and it is easy to see that most of the higher charge-states arrive early.

![Figure 6.5-3; Charge-states 16-18 arrive almost equally much in the first three time windows.](image)

![Figure 6.5-4; Most of charge-states 19-21 arrive in the earliest time-window. Because of slow phosphor and change in time window, there seems to be still a lot of these charge-states in the latest time window.](image)
Chapter 7

Discussion

In this chapter a discussion about the results is given. Section 7.1 concerns the results obtained with ion plasma and section 7.2 the results obtained with accelerated ions.

7.1 Experiments with ion plasma

There were many problems to overcome before it was possible to obtain any results. Software had to be written, information about the system had to be checked and double checked and data had to be sorted out. After tests to verify that the methods used to extract results from the experiments was correct, we finally draw some conclusions.

7.1.1 Charge-state distributions

The first series show good stability in the CSD and the field correction is low which give good confidence in the result. The peak charge-state is +22 and the standard deviation for the shot-to-shot intensity variation of this charge-state is 8.0%. This implies that the focus of the laser on the target does not change critically for the first 15 shots, although there is a small tendency that the intensity of charge-states +25 to +27 decreases.

With an electrostatic analyser (ESA) we do not see higher charge-state ions than +25 with this laser energy and the peak is around +20 [16]. The TIS shows ions as highly charged as +29, which means that the parabolas have a spreading in space that are as much as four charge-states. As the parabolas are more tightly packed at higher charge-states, the overlapping to higher charge-states is larger than that to lower. This spreading would flatten the CSD and broaden it particularly towards the higher charge-states. This is clearly seen if we compare the TIS results to ESA results (see section 5.2 and 3.6). The spreading of the parabolas does not explain the shift of the peak to a higher charge-state.

The second series is very unstable, the peak charge-state fluctuate between +20 and +25 with a mean value of +23. This is probably because the camera cuts all pixel intensities under 24 and because of the high field correction. A high field correction reduces our confidence in the calculations.

7.1.2 Energy distributions

The energy distributions analysed originate from the peak charge-state of the series, i.e. charge-state +22 for series one and charge-state +23 for series two. For the first series the peak energy is around 4 keV/z and for the second around 8 keV/z. Previous measurements done with an ESA show a peak at about 2keV/z [D].

The difference in peak energy between the two series can be due to two things, the sensitivity of the camera used and the uncertainty the high field correction indicates. The camera has a range from 0 to 255 in pixel intensities, but it cuts all values under 24. The number of ions that will hit an area equivalent to a camera pixel area reduces at higher electrostatic and magnetic fields, leading to a
higher probability that the intensity on a pixel will fall below the threshold 24. This means that there might be some ions with lower energy per charge, but these are not registered because the camera disregards this information.

The threshold for sensing the ions is indicated if all intensity values of 0 are changed to be 23. This is shown in Figure 7.1-1 and Figure 7.1-2 and the change in the distribution caused by this change is obvious. For the first series it does not change much (Figure 7.1-1), but if there were some ions with lower energy than 3 keV/z, this could possibly mean a change in the peak energy. In that case the energy distribution would agree better with the measurements done with the ESA.

The high field correction means that the fields acting on the ions differ considerably from the fields applied. This induces faults in the calculations. To match the calculated parabola with the measured, one can change both the B- and the U-value (equation 4.3). Changing the magnetic field to a higher (theoretical) value will have the same effect on the calculated parabolas as changing the electric field to a lower (theoretical) value. It is impossible to know how the fields should be adjusted without doing any closer measurements of the fields in the TIS, preferably during operation.

![Energy distribution](image1)

**Figure 7.1-1:** For the first series the difference between having 0 or 23 as lowest pixel intensity is not as big as for series two. From the shape of the curve it is possible that there are some ions with lower energy per charge than 3 keV, that are not seen because of the sensitivity of the camera. Then the peak energy would move to lower energies and agree better to previous measurements.

![Energy distribution](image2)

**Figure 7.1-2:** There is a big difference in the energy distribution for the second series if the lowest pixel intensity is 23 instead of 0.

### 7.1.3 Ion collector signals and time - intensity diagrams

The signal from the IC is very low compared with signals from previous measurements done with a Faraday cup (FC). A general rule [24] for ion plasma is:

\[ j \propto \frac{1}{l^3} \quad \text{(7.1)} \]

\[ I = j \times \text{Area} \quad \text{(7.2)} \]
where \( l \) is the distance from target to ion collector, \( I \) the ion current and \( j \) the ion current density. For a FC with diameter 30 mm placed 1 meter from the target we usually get around 50 mA. This gives a current density of 102 A/m², which at 1.56 meter would give:

\[
j_{1.56} = \frac{j_{1.0}}{1.56^3} = 27 \text{ A/m}^2.
\]

(7.3)

The current density from the ion collector is calculated using:

\[
j = \frac{V_c}{S_c \cdot R_\alpha \cdot \delta}
\]

(7.4)

where \( V_c \) is the voltage recorded, \( S_c \) the collecting area, \( R_\alpha \) the resistance over which the signal is taken and \( \delta \) is the current increase caused by secondary electrons escaping from the collector. Taking realistic values for these parameters gives:

\[
S_c = 4.81 \text{ cm}^2 \\
R_\alpha = 50 \text{ } \Omega \\
\delta \approx 2 \\
V_c = 0.1 \text{ V}
\]

therefore:

\[
j = 2.1 \text{ A/m}^2
\]

This is 10 times lower than expected. The lost current could be due to electrons not being reflected by the field before the IC, i.e., the suppression voltage was not high enough. In this case we would expect the signal to be distorted and go to zero in several places, but the shape of the IC diagram resembles the shape we usually obtain from the FC. This phenomena is difficult to explain.

Despite the low intensity of the signal, the integration in the IC signals and in the velocity-intensity diagrams, over the time when the high charge-states arrive, show good correlation. For the first series this time is 3 - 8 µs and for the second 3 - 5 µs. The fact that the second series does not correlate as well as the first one can be explained by the way the intensity-velocity diagrams are achieved. TP-imager does not include any field correction (see section 4.2.5) in the calculations of the velocities, which means that the diagram can be displaced in time.

The difference in time between the two series could be assigned to the camera sensitivity again. If the integration time in the IC signal for the second series was to be taken over the same time as for the first series, the two signals should be in the same range if there were approximately the same number of ions. See Figure 7.1-3. This indicates that there are ions impinging on the MCP, which we do not see. This confirms the theory that we lose some information because of the threshold of the camera.

When the laser creates a deeper crater in the target, as for the last shots in series 2, one would expect a smooth decrease of the integration value (total charge). Instead there are large fluctuations, but the main direction is towards lower values.
7.1.4 Sources of errors

Calculations - all values are transformations between quantities, originating from pixel positions and intensities from the camera. The value of the different charge-states in a CSD are calculated as the sum of \( dQ/dE_i \) times \( dE_i \) where \( dE_i \) is the difference between two consecutive \( E_i \) values. This gives a larger \( dE_i \) for higher \( E_i \) and this weighting might not be completely correct.

Field corrections - the Prague program only incorporates this in the magnetic field. This changes the calculated velocity lines but not the \( E/\gamma \). In TP-imager the correction lies in the \( y \)-value by changing the pixel/mm value. For the parabolas this will make the same amount of correction because of the relation \( x = U/B^2 \cdot \gamma^2 \). The velocities in the images and in the velocity-diagrams do not include this correction. However, the \( E/\gamma \) lines are calculated with a correction so the two equations \( E/\gamma = \omega E/U/\gamma \) and \( E/\gamma = B^2/\omega E/\gamma \) give the same value for a given point.

Camera values - there are no pixel intensities between 0 and 24 in the images from the Tektronix camera. For higher fields (\( E \) and \( B \)) the spreading of the parabolas are greater and therefore give less intensity to each pixel. From Figure 7.1-1 we see that the threshold for detection may be too high in the low energy region. This can lead to a very significant number of ions not being registered, and the resulting plasma energy distribution is lost at lower energies.

Parabola spreading - here we can see up to charge-state +29, with other methods the limit is +25. This is due to parabola spreading which can have a big effect on the analysis. Since the profile is only one pixel broad, but there is some spreading of the measured parabolas in space, we do not get the entire intensity. The spreading of the parabolas can vary from charge-state to charge-state. This means that we don’t measure the same percentage of the intensity for each charge-state and the following distributions can be wrong.

Conversion from intensity to amount of current - the intensity of one pixel is taken as \( dQ/d\gamma \), where it is more correct to take \( I = dQ/d(\gamma dx) \). But we can not properly evaluate \( dQ/d\gamma \) with constant \( y \) so we assume it to be an arbitrary constant.

Screen limit - especially for the second series a lot of ions land outside the screen. This will give an incorrect CSD concerning the lower charge-states. It also makes it difficult to obtain a good comparison between the intensity - time diagram from the TP-imager and the ion collector signal.

MCP sensitivity - as explained in chapter 2.5.3, the MCP consists of a channel plate and a phosphor screen. The ions impinge on the channel plate and causes an avalanche of electrons to hit the phosphor screen which then emits light. If the ions have too low energy they can not start this avalanche and will not be recorded by the camera. The ions must have higher energy than the threshold of the MCP. This might explain why the lower charged ions have a high signal in the ion collector signal, but do not
show very much in the TP images. Since they only have the kinetic energy and not so much ionisation energy to give the channel plate it is harder to activate the MCP. This is due to the secondary electron coefficient not being properly equal to 2, as we have assumed.

Other uncertainties - the measuring ensemble of the MCP, phosphor screen and camera have been assumed to be linear to the charge of the ion.

7.2 Experiments with ion beam

Three methods have been used to analyse the recombination; taking the ratio of main peak to total intensity along a parabola, along a velocity line and integrating between horizontal lines in the entire image. For the recombination in time the method with velocity lines is the most trustworthy. This is because of the decay time of the phosphor in the MCP, which makes the parabola method somewhat uncertain. The method using integration between lines is not completely reliable because the images are rotated approximately 6 degrees which can not be adjusted when this method is used.

Recombination can be due to charge-exchange processes with residual gas ions, or capture processes for free-electrons released from the gas or the vacuum chamber and held in the beam potential well. Furthermore, free electrons can be produced by X-ray and UV emission from the laser plasma.

7.2.1 Recombination in time

All analysed images include fast ions, even if the time window is late. By comparing the velocities of the fastest and slowest ions seen in each image, we can calculate which ions (in time) are recorded for the different gates on the camera (see Figure 7.2-1). This overlapping is due to two effects:

1. The decay time of the phosphor in the MCP is longer than the gating window.
2. The camera may be pre-triggering.

The largest problem is the phosphor, where the current of the ions are converted to light which is recorded by the camera. If the decay time of the phosphor is faster than the time windows set in the camera, the overlapping would be less than one time window. Ideally the decay time should be less than one µs. The exact value of the decay time for this phosphor is not known.

The analysed images have two different time windows, the first five shots have a 2 µs gate and the last four 4 µs. When the camera is gated for a longer time it will record more intensity, but since the phosphor decays exponentially it is not correct to divide the intensities from the longer time windows by two. If the phosphor decay time was much less than 2 µs this would have no effect.

<table>
<thead>
<tr>
<th>Gating (µs)</th>
<th>Appearing in image</th>
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<tbody>
<tr>
<td>28-32</td>
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<td>24-28</td>
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<td>6-8</td>
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<td>0-2</td>
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</table>

\[ t | μs \]

Figure 7.2-1: Because of long decay time of the phosphor, the different gated time windows of the camera show big overlapping in reality.
The parabola method gives a recombination of 55-75%. Later time windows have more recombination than earlier. The intensity profiles show 4-5 peaks, which means that the ions can recombine up to 3-4 times.

Following a parabola, the recombined ions will always be faster than the uncombined. They originate from higher charged ions at extraction and therefore received more energy. Thus, we will see a higher percentage, than is true, of uncombined ions of each charge in the later time windows and less for the earlier. This is not the best way to measure total recombination.

The velocity line method give a recombination of 60-80%. Later time windows and higher charge-states have more recombination. Intensity profiles show that the ions recombine 3-4 times. This is a better way to measure recombination in time, because the camera registers all points along this line for an equal time. Therefore the uncertainty about the phosphor is eliminated.

Integrating between horizontal lines give 60-70% recombination with a little increase in time. With this method it is not possible to see how many times the ions recombine. The largest uncertainty with this method is the rotation of the images. The divisions were always made in favour of the uncombined ions, so the "true" recombination might actually be a little higher.

7.2.2 Recombination with different laser energies

These images were taken with the Tektronix video camera, so again there is a problem with the cutting all pixel intensities under 24. In addition, there were not many images taken under these conditions and the statistical data for these results is not more than two images. The images were taken as shot number 17 and 19, so the small amount of high charge-states can be an effect of the cratering of the target. There is no gating of the camera, so the phosphor decay time is not relevant.

The recombination fraction was 40-80% and the result show less recombination for higher charge-states at lower laser energies. This can be explained by two effects:

1. For a higher laser energy, more gas can be desorbed from the walls of the vacuum chamber (causing higher pressure) and a higher ion current leads to a deeper potential well to capture electrons.

2. The high charge-state production is not large, especially for the low laser energy. The amount of recombined ions in each recombination group might not be big enough to pass the threshold of the Tektronix camera. This results in a skew picture with only uncombined ions.

7.2.3 CSD in time

The CSD for the different time windows does not vary as expected. If the camera gating was exact, and the camera only recorded ions reaching the MCP within the gate, the different charge-states would only occur in one or maybe two time windows. The CSD overlapping occurs because of the initial plasma energy spread and the decay time of the phosphor. In particular high charge-states can be seen in all time windows. The lack of resolution of the individual peaks also induces uncertainties.

It is certain that the high charge states arrive first. Using the TIS could be a very simple and fast method to see the approximate CSD in time (since only the uncombined ions are considered here), but this requires a better defined gating.

7.2.4 Sources of errors

Phosphor decay time - the phosphor in the MCP decays exponentially. This decay time determines for how long time the camera will "see" an ion after it impinges on the MCP. In this case the decay time is
much longer than the time windows of the camera and thus the camera will record the fast ions in more than one time window.

*Length of time window* - the longer the time window is the more intensity is recorded by the camera. But the intensity-time relation is not linear as the phosphor light decays exponentially. This makes it difficult to compare images recorded with different time windows.

*Resolution of peaks* - to make a CSD from uncombined ions or calculate the ratio of the main peak to total intensity of an intensity profile, it is necessary to distinguish the peaks. This is not always possible.

*Parabola spreading* - is not as bad as in the plasma case, but it still exists.

*Camera values* - for the attenuation analysis, the Tektronix camera is used and it cuts all pixel intensities under 24. This can cause low intensity peaks to disappear and the resulting analysis to be unreliable.

*Vacuum* - the vacuum in these experiments was just below $10^{-5}$ mbar. In earlier experiments it was shown that the recombination increases dramatically around this value. This means that recombination in the real ion source can be slightly less. There is so far nothing published to show the relation between vacuum level and recombination rate. Common sense say that higher vacuum give more molecules for the ions to recombine with.
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Chapter 8

Conclusions

With a TIS it is possible to resolve the $E/z$ and $P/z$ phase space with one laser shot. This is a fast method compared with an electrostatic or magnetic spectrometer which needs 50-100 shots to give a full charge-state and energy distribution. The TIS makes it possible to obtain charge-state and energy distributions as a function of laser pulse variation. It is also easy to measure the recombination rate in the ion beam.

It has not been possible to analyse all the data obtained from the experiments due to lack of time. However, during this study some limitations of the TIS was found, and it would be preferable to forego further analysis and first improve the TIS as proposed below. Then another set of experiments could be performed, carefully planned to achieve the wanted results.

The following ion plasma/beam characteristics have been measured:

- The charge-state distribution as a function of
  - shot-to-shot variation (plasma)
  - focal position with respect to target (plasma)
  - time within the beam pulse (beam)
- Energy distributions in plasma
- Recombination rate in ion beam
  - inside one charge-state (along a parabola)
  - as “history” of one charge-state (along a velocity line)
  - total recombination
- The number of times the ions recombine after extraction

The analysis show:

- The Laser Ion Source provide high charge-states (up to 29+) with a peak around 22+ (in comparison with 24+ and 20+ by multi-shot methods)
- The intensity of a single high charge-state varies from shot to shot with a standard deviation of 8%.
- The focus of the laser on the target does not change critically for the first 15 shots.
- In the accelerated beam around 65% of the ions recombine between extraction and detection.
- The ions recombine up to 3-4 times during their journey.

Important points:

The best way to measure recombination is to integrate between lines, where the lines divide the image in recombined and unrecombined ions.

Since the CSD from the TIS is derived from an image recorded by a CCD camera (the ions impinge on an MCP and are transformed to light by a phosphor screen) there is a long chain of possible non-
linearities. This can be evaluated but the CSD derived with the electrostatic analyser must be considered as more reliable.

The measurements suggest that the width of each parabola a group of ions with one charge-state create, is of the order of 10 calculated parabolas. If the recombination of the ions was lowered somehow, the parabola spreading would decrease and some of the uncertainty in the plasma analyses would disappear.

**Possible improvements to the TIS:**

- Better vacuum and changed geometry of the beam transport. Needed if the recombination measurements are to show the quality of the LIS as it usually operates.
- Easier alignment.
- Better field calibration. To reduce faults induced by the calculations and obtain an easier match of the calculated parabolas with the measured.
- Better gating of camera and faster phosphor screen. To be able to do interesting measurements in time, such as CSD and recombination.
- Camera without low level threshold. Very important if any quantitative results will be obtained.
- Big MCP. To be able to have a better resolution (deflect the ions more) without losing information (ions land outside the screen)
- More software. A possibility to integrate between lines need to be implemented and an easier way to change the constants depending on the geometry of the system. The software should also use the whole dynamic range of the images.

**Possible application of a TIS at CERN LIS:**

If the improvements above are accomplished, the TIS could, in addition to what have been analysed here, be used to answer the following questions

- What is the CSD after focusing the ion beam with solenoids?
- Are there more recombination in specific points?
- What is the energy spread in the main peak of a charge-state?
- How does the ion plasma/beam configuration change with distance from target?

Another important task for the TIS could be to help set the focus of the laser on the target.
References

Books and papers:


**Persons:**

[ A ] Richard Scrivens

[ B ] Alessandra Lombardi

[ C ] Leos Laska

[ D ] Klaus Langbein
Appendix A

Result-diagrams from experiments with ion plasma

The shots analysed for experiments with plasma are:

First series:

- 20059709
- 20059711
- 20059713
- 20059714
- 20059716
- 20059718
- 20059719

Second series:

- 21059712
- 21059714
- 21059716
- 21059717
- 21059719
- 21059721
- 21059723
- 21059725
- 21059727
- 21059729
- 21059731
- 21059732
- 21059734
- 21059736

The first six digits in the number tell what date the shot was made and the last two are merely a counter.

CSD for the analysed shots

Here are the charge-state distributions for all shots analysed in the two series. The different charge-states are along the x-axis and the intensity in arbitrary units along the y-axis. As seen the CSDs for first series are very stable from shot to shot, but in the second series there is a large variation. A summary with all the CSDs for the shots in series one and two are shown in section 5.2.

First series

![Charge-state distribution shot 1](image1)

![Charge-state distribution shot 3](image2)
CSD for charge-state 15 - 27, from all analysed shots in first series.

Second series
CSD for charge-states 16-27, from all analysed shots in second series.
Energy distributions for the analysed shots

These distributions are for one charge-state in one shot each. They show the energy distribution within the group of ions that have the same charge-state when they are detected. This distribution should be as spiked as possible. Then most of the ions can be accelerated with the RFQ.

First are distributions from all analysed shots in the series, originating from charge-state 22 in the first series and charge-state 23 in the second series. After that comes energy distributions from all charge-states analysed in one shot. That is shot number three in the first series. This way it is possible to see how the energy distribution differ between shots and also between charge-states.

First series

Energy distribution for charge-state 22 in all analysed shots, first series.

Second series
Energy distributions for charge-state 23 in all analysed shots, second series.

**Energy distributions in shot three, first series**
Comparison IC signal - TP time diagram

The TP time diagram is a time-intensity diagram obtained with the TP-imager program. It is an integration in the image the ions produce as they impinge on the phosphor screen, and thus the expected intensity signal. The comparison with the measured intensity signal (from the ion collector) show good correlation for the high charge-states (arriving early) in most shots. This implies that the technique used to obtain the TP diagrams are correct, and can be used for other investigations too.

The diagrams are grouped with the IC-diagram above the TP time-diagram for an easier comparison. First are all the diagrams from shots in the first series and then are the diagrams from the second series.

First series, comparison intensity diagrams
Second series, comparison intensity diagrams
Appendix B

Result-diagrams from experiments with ion beam

The shots analysed are:

<table>
<thead>
<tr>
<th>With gated camera:</th>
<th>Gate (μs):</th>
</tr>
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</tr>
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<td>16-20</td>
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<tr>
<td>23059742</td>
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<td>24-28</td>
</tr>
<tr>
<td>23059744</td>
<td>28-32</td>
</tr>
</tbody>
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<table>
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<th>Different laser energies:</th>
<th>Energy (J):</th>
</tr>
</thead>
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<tr>
<td>21059784</td>
<td>24</td>
</tr>
<tr>
<td>21059786</td>
<td>13</td>
</tr>
</tbody>
</table>

The first six digits of the number tell what date the shot was made and the last two are a counter that starts from 00 each day.

Intensity profiles from gated camera

Unrecombined ions

These profiles are taken over the horizontal line of unrecombined ions and should be the CSDs in time for the shots. Because of the phosphor and the camera (as discussed in section 7.2) it is not possible to use these profiles as CSDs, as intended, and additionally the peaks for the different charge-states are not easily distinguishable.
Intensity profiles along parabolas

Again the peaks are not easy to distinguish. From comparison with lines in the images, it is possible to say where the main peak is in each profile, but for the other peaks it is very difficult.
Appendix B

Intensity profiles along velocity lines

Same as for the other intensity profiles with the gated camera, the peaks are not clearly distinguishable. Yet, it is possible to make an estimation of how large percentage of the ions are uncombined by deciding where the main peak starts and ends.

Velocity line +10

Velocity line +15

Velocity line +20
Intensity profiles comparing two energies

Unrecombined ions

These are the profiles of the horizontal line where the unrecombined ions are. In the first profile, for 24J, we can see peaks for charge-states +1 to +23. In the second profile, for 13J, the highest charge-state is +21.
Intensity profiles along parabolas, two energies

In this case, it is easier to see the different peaks. The images, from which these intensity profiles are taken, are taken with the Tektronix camera, which means that not all the intensity from the ions are recorded (as discussed in section 7.1). Therefore some peaks might be missing. Here it is possible to see how the peaks in the different parabolas move further away from the origin (of the parabolas) as the charge-state of the parabola increases. This means that the energy per charge decreases.

Energy 24J

Energy 13J
Intensity profiles from velocity lines, two energies

Again the peaks are more easy to distinguish, than for the gated images.

Energy 24J

Energy 13J
Appendix C

LabView Program

This program was written by the author, and will be used to diagnose the Master Oscillator - Power Amplifier during its construction and when it is completed.

Laser pulse statistics

This program will continuously take a trace from an oscilloscope, smooth the curve (number of points selectable) and calculate noise, FWHM, maximum of the curve and standard deviation of max.

The noise is calculated as the maximum difference between the original and smoothed curve divided with the maximum of the smoothed curve;

$$\frac{|X_i - S_i|_{max}}{Max}$$  \hspace{1cm} (C.1)

where $X_i$ is the point of the original curve and $S_i$ is the corresponding point of the smoothed curve.

Max is the highest value of the smoothed curve.

FWHM is calculated from the smoothed curve as the number of points, between the two values that is equal to half the maximum value, times the time between points.

Standard deviation of max is calculated as

$$\sigma = \sqrt{\frac{\sum x_i^2}{N} - \bar{x}^2}$$  \hspace{1cm} (C.2)

where $x_i$ is the maximum of the latest smoothed curve and $\bar{x}$ the mean value of all maximums recorded. The mean value is recalculated before every calculation of std dev.

The averages of these values are calculated for every shot, every good shot and the last 100 shots. A shot is good if the noise does not exceed the “Max deviation” which is 10% as default, but can be set to desired value. If “Max deviation” is set to zero all shots will be counted as good.

Every n'th shot these averages can be saved to a file which will also contain Save nr, Pulse nr, Nr good shots and Good/Total shot ratio. It is also possible to save the original pulse trace every n'th shot and the values noise, FWHM and maximum for every shot (“Save statistics”). This last save option can take a lot of space and should not be run too long.

The number “Point smoothing” should be set high enough to smooth the curve when there are big ripples, otherwise the noise will be falsely low and the shots counted as good even though they are not.

The program runs at approximately 1Hz. If the pulse rate is slower the “delay in ms” should be set to an appropriate time to avoid that traces are read in more than once.

When moving to a new oscilloscope the global variables “GPIB address” and “Channel nr” must be set to their correct values. For the “Channel nr” 0 corresponds to channel 1, 1 to channel 2 and so on. The global variable “ns between points” must be set to the time between points of the oscilloscope. To do
this open the diagram window for Laser pulse statistics click with right mouse button on one of the boxes with the name of the variable you want to change, choose Find/Global definition and change the value there.

If you want to save the settings you have made, remember to save (do file/save in the window were you have made any changes). If you have changed a default value, for example GPIB address, click in the box with the value and choose Data operation/Mak Current Value Default.

Run the program:

Start LabView under Start\Programs\LabView
Open Laser pulse statistics.vi under C:\Motest\Run these

To run the program, push the “run arrow” in the upper left corner of Laser pulse statistics-panel.

To stop push the stop button. No variables will be reinitialised and if you don’t push “New run” before starting again, the new statistics will add to the previous.

To do a new run and start the acquisition again from zero, push “New run”. You can do a new run while running the program or after a stop. This will reset all the variables and the filepaths, but not the controls. If you are saving, you will have to enter new name(s) of the file(s).

To pause the program push the pause button. To restart push it again. The data acquisition will continue.

To make the acquisition slower, fill in a number in “Delay in ms”. This is necessary if the laser is running at lower rate than 1Hz. Otherwise the program will read the traces more than once, and the statistics might not be correct. You can change this while the program is running.

To set the acceptable noise level, fill in a number in “Max deviation”. This decides which shots are good and is by default 10%. You can change this while the program is running.

To set the number of point smoothing, fill in a number in “Point smoothing”. This will be the number of points before and after the actual point that are included to give an average and smoothing. That means if you write 5, you will get 11 points smoothing. You can change this while the program is running.

Save averages and pulse trace:

The saving is off as default. To start save the averages and/or the pulse trace push the switch to ON. Decide how often you want to save. Remember that the program is running at approximately 1Hz as fastest.

Save average: If you choose to save, a filedialog will ask for the file name and path when you run the program. Write for example C:\Temp\240497.av . If you write the name of an existing file in the “File path” box before you start, there will be no new header.

Save pulse trace: Write the name of the file path. Ex C:\Temp\2404. The program will automatically put the first pulse in file 2404000, the second in 2404001 and so on. If you don’t write any filename the file will be saved in a default directory.

Save statistics: Saves in the same way as “Save average”. The filedialog will ask for the path for “Save statistics each shot”. Don’t use this too long periods, since the file can get very big.

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Appendix D

Emittance

One way to measure the beam quality of an accelerated particle beam is to calculate the emittance [8]. By strict definition, the beam emittance is related to the pattern that the beam particles occupy in the six-dimensional phase-space. The phase-space is defined in classical mechanics as the space of generalised positions and momenta, defined from the Lagrangian [25] as:

\[ q = \frac{\partial L}{\partial \dot{q}} \]  
\[ p = -\frac{\partial L}{\partial \dot{q}} \]  

In accelerator physics, a simplified phase space is often used. Then two important assumptions are made [7]:

- The three pairs are not completely decoupled, and the longitudinal projection of the pattern has no meaning for the quasistationary beam. Only the transverse projections are of interest here.
- The transverse motion is slow compared to the velocity in the beam direction and nonrelativistic calculations can be made.

This means that the transverse linear momenta, which are the interesting ones, can be substituted by:

\[ x' = \frac{dx}{dz} \]  
\[ y' = \frac{dy}{dz} \]

These are the tangent values of the divergence angles for the particle trajectory and the commonly used two-dimensional emittance is calculated from the patterns in the \((x, x')\) and \((y, y')\) planes. A typical pattern is shown in Figure D-1.

There are two conventions to quantify the size of the emittance [7]. One can either directly take the area occupied by the emittance pattern and express it in [mm mrad] or [m rad], or divide the area with \(\pi\). The way to express the emittance in the second convention is not completely clear. Some use \([1/\pi\text{ mm mrad}]\), while others use the same as in the first convention.

The reason for the second convention is that the emittance pattern most often has an elliptical shape. Then the emittance can be deduced directly from the product of the two semiaxis'.

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As if this confusion about the emittance would not be enough, there are also three different ways to define the elliptic area [7].

- There are the 100%-emittance, where the ellipse contains all the particles.
- The 95%-emittance, with 95% of the particles in the ellipse.
- The statistical root-mean-square (RMS) emittance, where the area is one (in electron machines) or two (in proton machines) standard deviations from the beam centre.

In the third definition, the emittance is calculated as:

$$\varepsilon_{RMS} = c \cdot \sqrt{x^2 \cdot \chi^2 - (xx')^2}$$  \hspace{1cm} (D.5)

where

$$c = 1 \text{ or } 2$$  \hspace{1cm} (D.6)

The horizontal line denotes the mean value of the position and/or trajectory angle of the particles. The disadvantage of these statistical values is that the actual beam fraction contained in the ellipse is not generally known. It depends on the distribution of the beam particles.

The concept of emittance offers one more source for confusion. If the particle beam is further accelerated, the emittance will shrink, because for given transverse velocities the longitudinal velocity has increased. This effect disappears if the emittance is "normalised" by:

$$\varepsilon_{\text{norm}} = \frac{\nu}{c} \cdot \sqrt{1 - \left(\frac{\nu}{c}\right)^2 \cdot \varepsilon}$$  \hspace{1cm} (D.7)

Where $\nu$ is the particle velocity and $c$ the velocity of light in vacuum. The particle velocity is calculated from the acceleration voltage used.

The normalised emittance of a beam is constant as long as only conservative forces are acting on the particles and the two planes of observation are truly decoupled. This is called Liouville's theorem and
can only be applied to the actual emittance pattern. It cannot be applied to the so-called effective emittance (calculated from the ellipses or as RMS) as discussed above.

From the shape of the ellipse, it is possible to see how the particle beam is behaving. A beam is divergent if its emittance pattern mostly extends from the third to the first quadrant in the coordinate plane. If the pattern mostly extends from the second to the forth quadrant, the beam is convergent. The beam is focused if the pattern is concentrated along the angle coordinate ($x'$ or $y'$) and roughly parallel if the pattern runs along the positional coordinate ($x$ or $y$). These emittance patterns are shown in Figure D-2.

Figure D-2: The shape of the emittance pattern tells if the beam is a) convergent, b) focused, c) divergent or d) parallel. To obtain a convergent or parallel beam, focusing magnets must be used.
The end.