LASER DIAGNOSTICS OF A ONE-DIMENSIONAL ORDERED ION BEAM.

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A novel method to detect ordering within a one-dimensional ion beam is proposed. The method exploits detection of fluorescence induced by two laser beams which simultaneously cross the ion beam. Appearance of correlation in fluorescence signal while moving the distance between the laser beams is indication of ordering in the beam.

I. INTRODUCTION

The possibility to observe ordered structures within an ion beam has met the interest of the community of accelerator people [1]. One of the crucial problems in this new research field is the diagnostic of an eventual ordered state for the ion beam. Experiments carried out in ion traps have shown that a record of crystallization is achieved by observing the fluorescence signal of ions through CCD camera [2]. Unfortunately, this technique cannot be applied straight away to accelerators since ions are traveling at relatively high velocity.

It is the purpose of this paper to show a method to detect ordering of an ion beam for one-dimensional ion structures .

II. THE DIAGNOSTICS DEVICE

Consider the simplest structure that is expected to be formed in a storage ring: a string of ions [3]. Typical values of interparticle spacing for the string configuration lie between s=10-100 µm; for the following we shall assume s=50 µm.

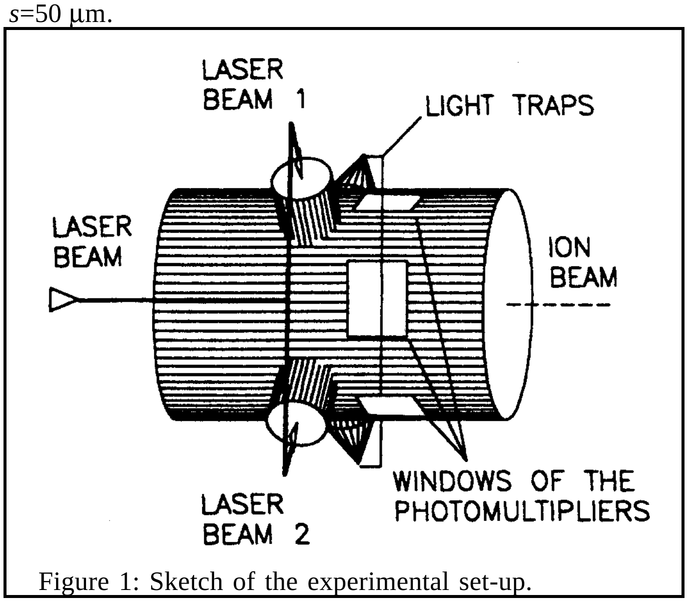

Figure 1: Sketch of the experimental set-up.

A pulsed laser - resonant with the traveling ions - is split in two parts, which simultaneously cross the ion beam at right angle at two nearby positions along the storage ring (see Figs. 1,2). This laser-to-ion crossing area is followed by four photomultipliers, which detect the photons emitted by the ions that have previously been excited by the laser beams.

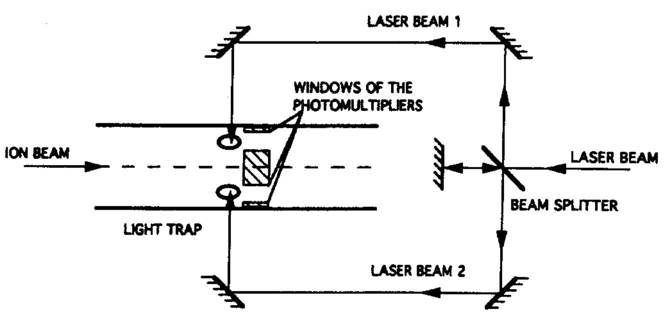

Figure 2: Layout of the experimental set-up.

The signals recorded by the photomultipliers are analyzed when one laser beam is moved with respect to the other one. In the absence of ordering, no correlation in fluorescence signals should be recorded while changing the relative distance of the two laser beams. On the contrary, if a string were obtained as a result of cooling, a strong correlation between the signals should be observed. Suppose that one of the four photomultipliers detects the fluorescence of an ion excited by one of the laser beams. If one of the other three photomultipliers detects a simultaneous fluorescence signal, it means that the other laser has interacted with another ion in the string, in turn indicating that the distance between the two ion-to-laser crossing points is an integer multiple of the string interparticle spacing. Then, by slightly moving the second laser beam, the correlation signal should vanish. A sort of periodical dependence on the distance between the laser beams should appear.

At non-zero temperature, ions are expected to oscillate both in the transverse and longitudinal directions (incoherent motion). Moreover, for a string longitudinal oscillations of equilibrium positions can also occur (coherent motion) through long-range waves. For the diagnostic system concerned through this paper the distance between the two laser beams can be chosen to match interparticle spacing of the string. In this case, the effect of coherent motion is ineffective as the nearest-neighbor spacing is relatively uniform. The effect of long wavelength on interparticle oscillations is negligible for a relative distance of a few lattice steps. An analytical evaluation of this effect can be found in Ref. [4]. Short

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wavelengths mostly affect the fluctuations in interparticle spacing, δs. Based on Ref. [4], a rough estimate holds: $<\delta s^2>/s^2 \sim 1/\Gamma$, where Γ is the plasma parameter for the ion beam (ratio between average neighboring ions Coulombic energy and thermal one). When the ion beam is being cooled δs becomes even lower than s; as an example, at $\Gamma = 100$, $\delta s = 5$ μm. As distance between the laser beams increases, the correlation signal becomes progressively weaker.

The configuration of the diagnostic device can also compensate for a possible influence of transverse oscillations. Since the laser beams cross the string perpendicularly and their spots are small enough that they do not overlap, the ions suffering transverse oscillations in the direction of the laser can always be resonant, irrespective of their coordinates along that axis. Ion oscillations in direction orthogonal to both the laser and the string could in principle move the target ion outside the laser beam spot. To avoid this effect - and the consequent less efficiency - the laser beam can be focused by a cylindrical lens. This optical element can be arranged to produce a focal segment orthogonal to the directions of both the laser and the string. In this way the locations where the laser beams impinge on the string are two thin regions; these can be as wide as several hundreds of microns in one dimension without overlap between them. Transverse oscillations of a very cold ion beam are expected to be lower than this value.

A single ion of the beam interacts with the laser beam for very short time, t_{int}. The probability of excitation to the upper level $P(t_{\mathrm{int}})$ is:

$$P(t_{\mathrm{int}}) = \left(\sin \frac{w_R t_{\mathrm{int}}}{2} \right)^2$$

where ω_R is Rabi frequency for the transition under consideration, which is proportional to the square root of the laser intensity. Thus, a reasonable interaction probability requests a sufficiently high laser intensity to make up for the short interaction time. This is not a problem since pulsed lasers are several times as intense as the saturation intensity for the ions that could be laser-cooled and a good excitation probability (~1/2) can be achieved. Moreover the focusing lens increases the intensity of the laser beam at the interaction point.

III. MONTE CARLO SIMULATION

A Monte Carlo simulation was specifically developed to show the feasibility of the method. The simulation includes all the physical processes involved, such as excitation probability by the two laser beams, probability of spontaneous decay, geometrical acceptance of the detector system, filtering and quantum efficiency of the photomultipliers. Also considered are the finite size of the laser beams at the focalization points and the dynamic behavior of the system due to non-zero temperature of the ions in the beam.

For more details about the Monte Carlo simulation and the detection system see Ref. [5].

As a first example we shall consider the case of a string of $^{22}Mg^+$ ions circulating in the ASTRID Storage Ring (Aarhus) at $\Gamma = 100$ with $s = 50$ μm. Ion velocity is $\beta = 0.003$, which corresponds to a time of about 56 ps taken by an ion in the beam to travel a distance as big as interparticle spacing. A duration of 2 ps was chosen for the laser pulse. Figure 3 illustrates the fluorescence response as a function of the distance between the two laser beams. Appearance of fluorescence peaks is visible in the figure when the distance between the laser beams is an integer multiple of the string spacing. Also the results of simulation for a disordered beam with the same density as the string is shown; in this case a totally uncorrelated pattern is achieved and the fluorescence signal is related only to stray counting of the photomultipliers.

It is remarkable that a clear firm of ordering within the ion beam can be achieved with only 1 s acquisition time, i.e. much less than beam lifetime in the storage ring.

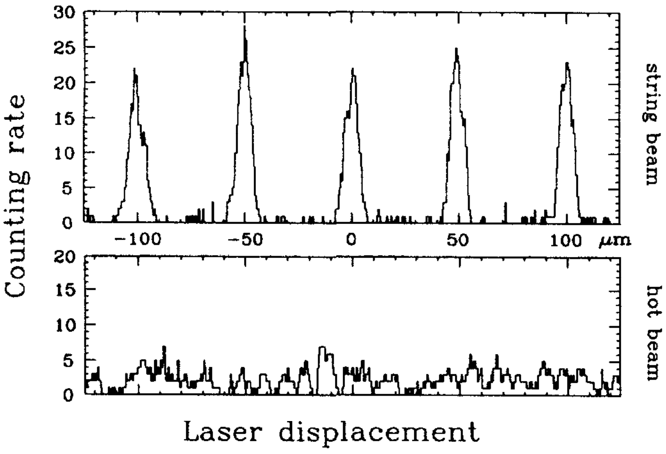

Figure 3: Pattern of fluorescence for $^{22}Mg^+$ ion beam at $\Gamma = 100$ for 1 s acquisition time.

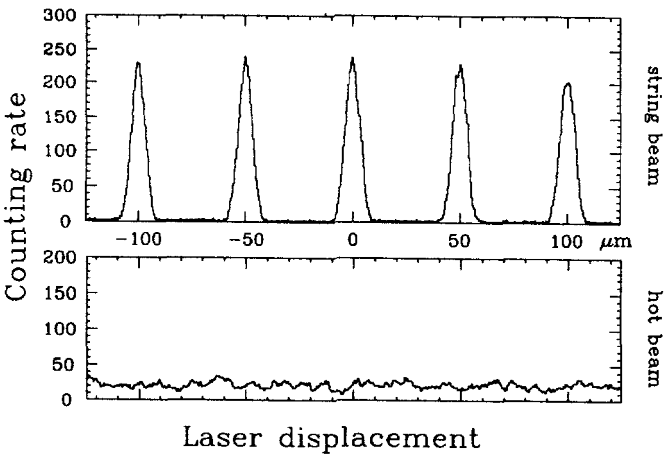

Figure 4: Pattern of fluorescence for $^{22}Mg^+$ ion beam at $\Gamma = 100$ for 10 s acquisition time.

The same simulation was carried out with the laser and beam parameters as for Fig. 3 but with a longer acquisition time (10 s). In this case correlation peaks have became more neat due to counting over a longer interval (Fig. 4).

A higher temperature of the beam, i.e. a lower plasma parameter, implies wider oscillations of interparticle positions.
As an example, Fig. 5 shows the correlation response at Γ=50.

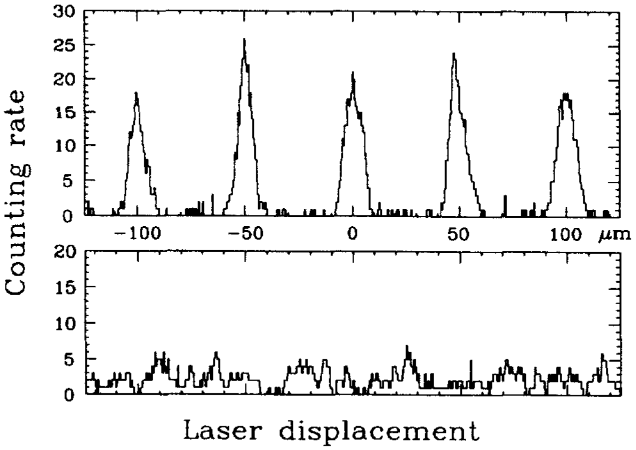

Figure 5: Pattern of fluorescence for $^{22}Mg^+$ ion beam at Γ=50 for 1 s acquisition time.

The simulation was carried out also for the case of $^7Be^+$ ion beam at TSR (Heidelberg) at Γ=100. Ion velocity is higher for this storage ring (β=0.05) and therefore one should resort to still shorter pulse duration for the laser. A commercially available 200-fs pulsed laser with some nJ/pulse was considered in the Monte Carlo and results are shown in Fig. 6. Correlation peaks are shorter, with respect to the case of $^{22}Mg^+$, due to lower quantum efficiency of photomultipliers and to the more complicated level structure of $^7Be^+$.

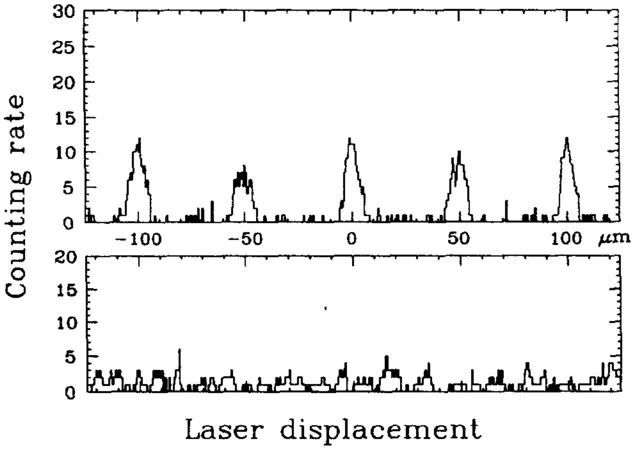

Figure 6: Pattern of fluorescence for $^7Be^+$ ion beam at Γ=100 for 1 s acquisition time.

Table I summarizes the important parameters for the previous cases.

Table I: *Important parameters for the simulation*

Storage ring	TSR	ASTRID
β	0.05	0.003
ion species	$^7Be^+$	$^{22}Mg^+$
wavelength	313 nm	280 nm
upper state lifetime	8.7 ns	3.5 ns
lower state lifetime	groundstate	groundstate
laser repetition rate	50 MHz	50 MHz
pulse duration	200 fs	2 ps

IV. DISCUSSION

It has been shown that the method is useful as a diagnostic tool to detect ordering in one-dimensional systems. The method enables to resolve the single-ion structure of the beam. Finally we wish to point out that all components of the system are commercially available and that the diagnostics could be easily implemented in one of the existing storage rings.

V. REFERENCES

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