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Optical system for Doppler cooling of trapped calcium ions

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Abstract—In the experiments involving trapped ions, the application of a cooling procedure is required. The optical Doppler scheme is one of the most commonly used methods for slowing down ions motion. In this paper we present an optical system sufficient for cooling calcium ions in such a scheme. The system allows also for optical detection of trapped ions.

Experiments with trapped ions require an efficient method for cooling and detecting the ions inside the trap [1]. In the presented experimental set-up [2] it is intended to investigate various collisional effects involving ions of different species, including atomic and molecular ones, for example: further ionization, dissociation, charge-transfer collisions, chemical reactions, elastic scattering energy transfer, etc.

The trapped ions will be slowed down using a sympathetic cooling scheme, which involves direct optical quenching of at least one species of ions forming the ensemble. For numerous reasons (atomic mass 40 close to many other ion species, easy evaporating, easy optical access) calcium ions were chosen as the cooling medium. To ensure efficient calcium cooling, two laser systems are necessary [3].

The application of two lasers is explained in Fig. 1, where a simplified scheme of energy levels of calcium ions is shown. Doppler cooling is ensured by the UV laser driving $4^2S_{1/2}$ – $4^2P_{1/2}$ transition, while the NIR laser is necessary to avoid trapping ions in the dark $3^2D_{3/2}$ state.

The apparatus consists of a linear segmented Paul trap placed in a vacuum chamber. The trap is equipped with an electron gun, oven providing a calcium beam, and source of a molecular beam (not used for calcium cooling). The optical part of the apparatus contains two laser systems (397 and 866nm) used for Doppler cooling and detection of calcium ions.

Both systems are external cavity diode lasers. As the lasers wavelengths tend to drift in time, stabilization schemes must be applied to provide efficient cooling.

As the UV photon momentum is higher than NIR and the S-P transition is much stronger than that of P-D, the fine tuning of a 397nm beam is more important than a 866nm one. This way, for a UV beam a more precise method of Pound-Drever-Hall [4] locking was used while for NIR, a simpler FM lock [5] scheme was applied.

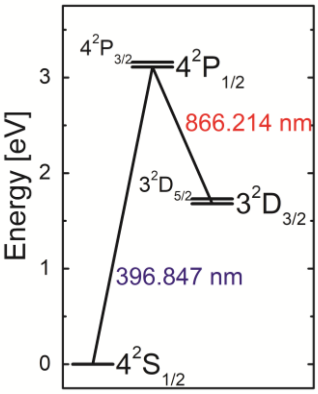

Fig. 1. A simplified energy level scheme of calcium ions. The wavelengths of the transitions applied in the cooling method are also presented. The cooling is based on red-detuning of the UV 397nm optical beam. The NIR 866nm beam is necessary to prevent ions from settling in a dark D state.

Both stabilization schemes use vacuum optical cavities made of ultra-low expansion glass (ULE), 150mm long each, providing a free spectral range of 2GHz and finesse of 1000.

The Doppler cooling efficiency depends on the UV laser detuning as presented in Fig. 2. The details of derivation of the curve can be found in ref. [6]. The efficiency can be understood as the rate of energy loss by the ion ensemble during the interaction with the laser. Positive values mean cooling the system (red-detuned laser) and negative stand for heating up the ions (blue-detuned laser). As the ions gain energy from the RF electric field, collisions with the residual gas, etc., the equilibrium energy of the ions depends on this rate. The efficiency also depends on laser beam power and geometry, number of ions, trapping potential, etc., so for simplicity, the graph in Fig. 2 has been normalized. From the graph one can find the optimum detuning to be below 50MHz, which is much lower than the cavity's FSR. Therefore, additional tuning of cavity length based on piezoelectric mounts is necessary.

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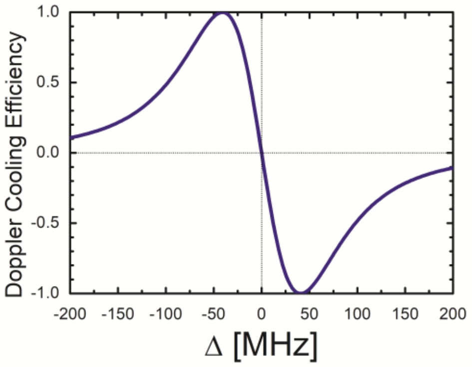

Fig. 2. Cooling efficiency of ions with the UV laser versus the detuning of optical frequency. The graph is normalized as the efficiency depends on numerous parameters besides laser detuning (see the text).

An overall scheme of the apparatus has been shown in Fig. 3, where the laser cooling optical system and detection system are also presented. The detection of ions uses 397nm fluorescence which enables imaging the ion ensemble using a CCD camera. The imaging system consists of two lenses enabling focusing the image, a mirror allowing for precise alignment of the camera, a narrow band pass filter to reduce the image background, and a CCD camera equipped with a quantum image intensifier. The system allows for recording images with a resolution of the order of 1μm.

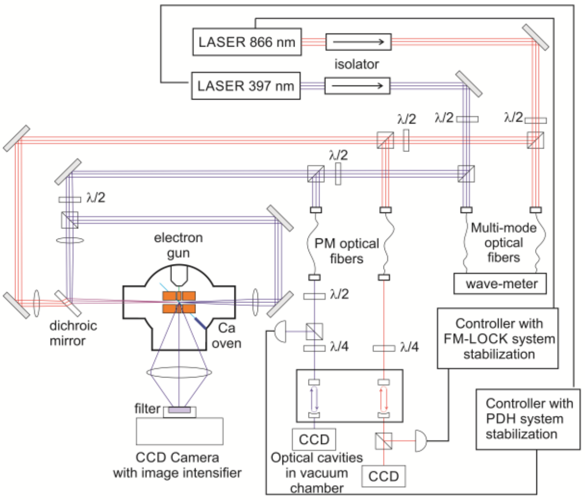

Fig. 3. A simplified scheme of the optical system of the apparatus. Some elements such as mirrors or lenses have been omitted for simplicity. UV and NIR laser beam sources are equipped with optical isolators. The optical beams are split into three paths: one going to the wavelength meter, one for the cavity used for stabilization and one going to the vacuum chamber containing an ion trap. The UV beam is additionally split into two counter-propagating beams to avoid photon pressure effects. Both UV and NIR beams are merged together using a dichroic mirror. Calcium ions are produced in electron-impact ionization of neutral calcium atoms emitted from the oven.

The presented optical system can be applied in various experiments involving calcium ions and multi-species ion ensembles (containing Ca^+). Before such investigations, the stability of the trap should be mapped, which enables optimal choosing of trapping parameters. To analyze such stability, the description of ion motion using Mathieu equations is applied [1]. The trap field can be written using the equation:

$$\mathrm{E}(x,y,z,t)=\left[\left(\frac{U_0}{R^2}\cos(\Omega t)+\frac{\alpha V_0}{2R^2}\right)x,\left(-\frac{U_0}{R^2}\cos(\Omega t)+\frac{\alpha V_0}{2R^2}\right)y,-\frac{\alpha V_0}{R^2}z\right], \tag{1}$$

where R is the trap radius (4.5mm in this case) Ω is the angular frequency of the RF field used for driving the trap. The α parameter of the order of 1 is a geometrical coefficient depending on trap construction. U_0 is the amplitude of the RF field and V_0 is the DC voltage applied to the outer segments of the trap providing ion confinement along the trap axis.

The ion motion is then described with the equations:

$$\ddot{x}=\frac{Q}{M}\left(\frac{U_0}{R^2}\cos(\Omega t)+\frac{\alpha V_0}{2R^2}\right)x, \tag{2}$$

$$\ddot{y}=\frac{Q}{M}\left(-\frac{U_0}{R^2}\cos(\Omega t)+\frac{\alpha V_0}{2R^2}\right)y, \tag{3}$$

$$\ddot{z}=-\frac{Q}{M}\frac{\alpha V_0}{2R^2}z, \tag{4}$$

where Q is the ion charge, M is its mass.

Such equations can be simplified using two dimensionless parameters, usually denoted with a and q. They are defined with the expressions:

$$a=\frac{Q\alpha V_0}{2MR^2\Omega^2} \tag{5}$$

$$q=\frac{QU_0}{2MR^2\Omega^2} \tag{6}$$

The motion equations, Eqs. (2-4), can be written in the form of Mathieu equations for the x and y coordinates and harmonic oscillator for the z coordinate:

$$\ddot{x}=\Omega^2(2q\cos(\Omega t)+a)x \tag{7}$$

$$\ddot{y}=\Omega^2(-2q\cos(\Omega t)+a)y \tag{8}$$

$$\ddot{z}=-2a\Omega^2 z \tag{9}$$

The stability of the calcium ions inside the trap has been investigated experimentally, which was possible by applying the optical system presented in this paper. The measurement involved ionization of a large set of atoms using 100eV electrons (single pulses of the order of a second). It was followed by optical cooling of the ions and tuning the trap settings towards the edge of a stability region until a complete loss of the ions. Examples of ion cloud images obtained during the measurement are presented in Fig. 4.

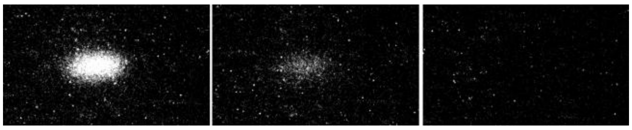

Fig. 4. Images of captured Ca^+ ensembles recorded over tuning the trapping parameters. The left panel shows a cloud of ions at settings far from the border of the stability region, the middle one presents approaching the edge and the right one shows an empty trap, set outside the stability region.

The measurement results are presented in Fig. 5 and compared with the theoretical stability diagram (obtained from analysis of Mathieu equation). The experimental points represent the settings, where ions were lost from the trap. Only one of the edges was investigated, as the ions are difficult to be trapped at higher q values due to the space-charge effects. The results obtained experimentally fully confirm theoretical predictions, which enables choosing optimal working parameters of the trap for future experiments.

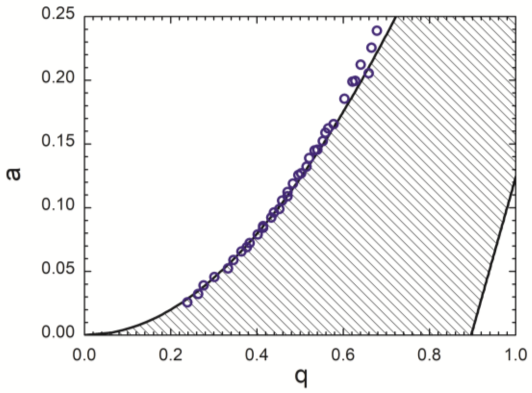

Fig. 5. A simplified stability diagram of the trap with experimental points of the edge of the stability region. The hatched area shows the stability region obtained from analysis of Mathieu equation. The measurements were performed at RF frequency of 1 MHz.

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