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Technical Notes

Simbuca, using a graphics card to simulate Coulomb interactions in a penning trap

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ABSTRACT

In almost all cases, N-body simulations are limited by the computation time available. Coulomb interaction calculations scale with $\mathcal{O}(N^2)$ with N the number of particles. Approximation methods exist already to reduce the computation time to $\mathcal{O}(N\log N)$, although calculating the interaction still dominates the total simulation time. We present *Simbuca*, a simulation package for thousands of ions moving in a Penning trap which will be applied for the WITCH experiment. *Simbuca* uses the output of the Cunbody-1 library, which calculates the gravitational interaction between entities on a graphics card, and adapts it for Coulomb calculations. Furthermore the program incorporates three realistic buffer gas models, the possibility of importing realistic electric and magnetic fieldmaps and different order integrators with adaptive step size and error control. The software is released under the GNU General Public License and free for use.

1. Introduction

In the last decades ion traps have become an indispensable tool for the measurements of a wide range of observables in atomic and nuclear physics [1]. Ion traps have not only pushed the limits for mass measurements [2] but are also used to prepare beams for post acceleration [3], to improve the emittance of ion beams [4], to assist decay studies [5], to improve the mass separation at ISOL-facilities [6] and for low energy weak interaction physics [7,8].

The WITCH experiment [9] (see Fig. 1), located at CERN/ISOLDE combines two Penning ion traps to measure the $\beta-\nu$ angular correlation coefficient a, which is sensitive to the weak interaction in nuclear beta decay [7,10]. Instead of detecting the difficult to observe neutrino, it measures the recoil energy of the daughter ions after $\beta-$decay. The radioactive ions are stored in a Penning trap instead of collecting them in a foil in order to be able to observe the full and unchanged recoil energy when they undergo decay. This recoil energy is typically only a couple of hundreds of eV. The WITCH experiment probes this recoil energy by applying a voltage barrier in the adjacent retardation spectrometer and counting the ions that overcome the barrier and reach the Micro Channel Plate (MCP) ion detector [11].

As WITCH aims to measure a with high accuracy (order of 0.5%), good knowledge and precise control over possible systematic effects is needed. The retardation spectrometer of WITCH (MAC-E filter type [12,13]) consists of a combination of electric fields created by 12 electrodes and magnetic fields from three magnets. To understand the behaviour of ions in this spectrometer a tracking routine for charged particles under the influence of electromagnetic fields was developed by Glück [14]. This routine, however, only gives correct information if one can characterise the source of the particles, i.e. the cloud of ions in the decay trap of WITCH. To this end a Penning trap simulation program, *Simbuca*, was developed.

Furthermore, optimization of the traps is necessary since WITCH needs a well-cooled source of ions. The temperature of the buffer–gas influences the width of the measured recoil energy

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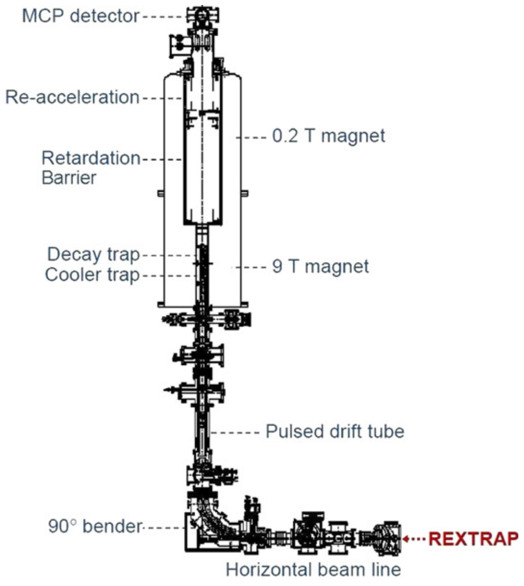

Fig. 1. Layout of the WITCH setup at ISOLDE.

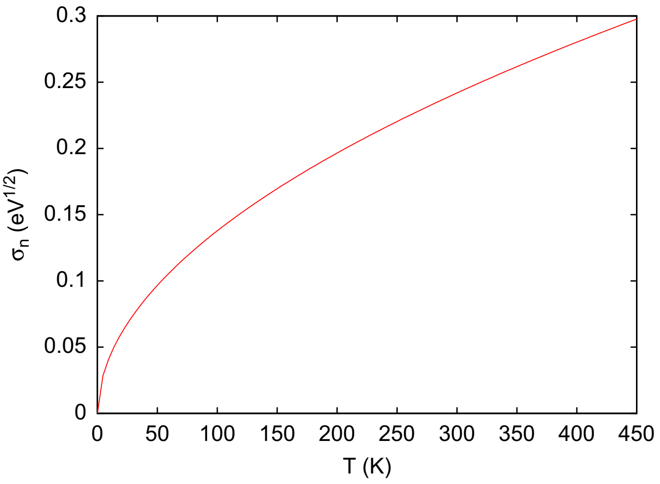

Fig. 2. Broadening of the response function depending on the temperature of helium buffer–gas atoms.

(see Fig. 2) as was simulated in Ref. [15]. Also other effects such as space-charge effects due to Coulomb interactions, the buffer–gas pressure, electrode potentials and excitations will affect the parameters of the ion cloud. Hence, these effects are also implemented in the simulation program.

The equations of motion of a single particle inside a Penning trap, also in the presence of a dipolar radiofrequency (rf) excitation field, are well known and can be solved analytically [16,17]. Ion clouds with high densities and low temperatures can be described as non-neutral plasmas and their properties are also well understood [18]. Such a weakly correlated cloud of charges is considered a plasma when the cloud is large in all its dimensions compared to the Debye length, $\lambda_D=\sqrt{kT/4\pi n^2}$, with T the temperature of the ions, n the density and k the Boltzmann constant. At the typical densities and temperatures which apply to the WITCH Penning traps or similar Penning trap systems like REXTRAP [3], one is far from the one particle picture but also not yet in the plasma regime. Since the equations of motion for a large number of interacting particles that do not form a plasma cannot be solved analytically, one has to use computer simulations to understand the behaviour of such ion clouds.

These effects were investigated for up to 500 particles in Ref. [15]. Since the calculation of the Coulomb force was done on a normal processor (or CPU) it was impossible to simulate more particles within a reasonable amount of time. With the *Simbuca* code that is presented here, this problem is eliminated by using the Graphical Processing Unit (GPU) to calculate the Coulomb interaction.

2. Penning traps

2.1. Penning trap principles

A Penning trap is a three-dimensional device in which charged particles can be stored and manipulated [17]. An electrostatic field of the form

$$\mathbf{E}=\frac{U_0}{2d^2}(x\hat{\mathbf{e}}_x+y\hat{\mathbf{e}}_y-2z\hat{\mathbf{e}}_z) \tag{1}$$

with U_0 the potential difference between the ring and endcap electrodes (see Fig. 4), $d=\sqrt{(z_0^2+r_0^2/2)/2}$ the trap dimension, r_0 the radius of the ring electrode and $2z_0$ the axial separation between the endcap electrodes in the case of a hyperbolic trap, confines the charged particles in the axial direction, while a strong axial magnetic field confines the particles in the radial direction.

The combination of these two fields leads to decoupling of the total motion in three independent eigenmotions, each with a specific angular frequency, ω_-, ω_+ and frequency ω_z (see Fig. 3). The following relations between these frequencies hold in an ideal Penning trap:

$$\omega_\pm=\tfrac{1}{2}\left[\omega_c\pm\sqrt{\omega_c^2-2\omega_z^2}\right] \tag{2}$$

$$\omega_c=\omega_++\omega_- \tag{3}$$

$$\omega_+\gg\omega_z\gg\omega_- \tag{4}$$

with $\omega_c=qB/m$ the so-called cyclotron frequency.

The three eigenmotions can be described as:

1. The magnetron motion emerges due to the interplay of the magnetic and electric field and causes a drift of the particle around the trap center in a plane perpendicular to the magnetic

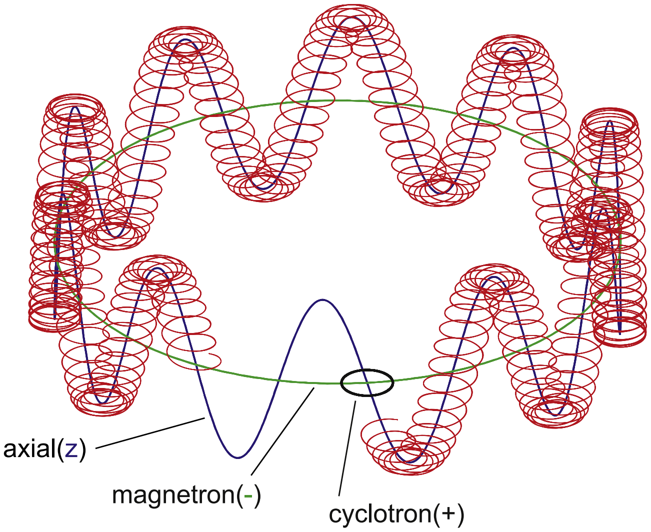

Fig. 3. The full motion of an ion in a Penning trap can be decoupled into three independent eigenmotions: the cyclotron motion, the magnetron motion and the axial motion.