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# On plasma neutralization of the ion beam

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**Abstract.** Simulation of the thermal motion of ions in a spherical bunch was performed on the basis of the molecular dynamics. The Yukawa potential was used to describe the ion interactions. Obtained data showed good agreement with results of theoretical investigation. The conclusion was done that INURA accelerator needs good plasma neutralization in order to keep transverse size of the ion beam.

## 1. Introduction

Currently, various installations for the acceleration of charged particles are one of the most important tools for the study of many fundamental and applied problems. For example, ion accelerators are used in thermonuclear fusion installations [1], they also are used to create and study so–called Warm Dense Matter (WDM) [2] and in many other important projects. In 2018 in Nazarbayev University (Nur–Sultan, Kazakhstan) ion accelerator INURA [3] was launched. This accelerator was designed and created in collaboration with LBNL (Lawrence Berkeley National Laboratory, USA) and TPU (Tomsk Polytechnic University, Russia). INURA is a pulsed high–current ion accelerator that generates an ion beam (protons and carbon ions) with a current of about 10,000 amperes, a duration of 80 ns (nanoseconds), and an energy of up to 400,000 eV. The INURA Accelerator is a multi–purpose research complex designed to conduct a wide range of basic and applied research. In particular, the ion beam formed by the accelerator is a unique and effective tool for the structural modification of various solid–state, including nanomaterials.

Ion accelerators are subject to general requirements, namely, the ion beam must be radially compressed to a small point [4]. In order to create a short ( $\sim$  ns) pulse with an energy input sufficient for the intended purpose, it is necessary to split the initially long pulse from the ion beam injector into shorter ones and then compress them more strongly in both transverse and longitudinal (temporal) directions. The main problem here is the spatial charge of ion beams, which creates repulsive forces inside the beams, defocusing them, preventing the transportation. The practical use of such ion beams is possible by neutralizing their spatial charge.

The neutralization is carried out by introducing free electrons into the positive ion beam. Almost complete charge neutralization can be obtained by plasma neutralization, i.e. in the



presence of plasma sources in the transportation channel. The general conditions for this are as follows: the density of the generated plasma should significantly exceed the density of the ion beam, and the thermal energy of plasma electrons should be small compared with the value of the potential energy of the beam. At the NDCX–I and NDCX–II installations, a ferroelectric plasma sources (Ferroelectric Plasma Source, abbreviated FEPS) were used [5–9]. The ferroelectric plasma sources are described in detail in [5–9]. In INURA accelerator, plasma neutralization of the ion beam will be carried out also using ferroelectric plasma sources.

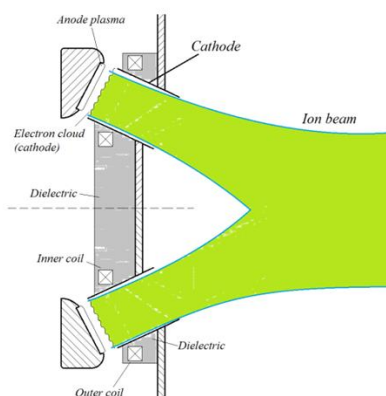
In recent years, computer simulation of both charged particle beams themselves and their interaction with plasma and targets has been developing. The interaction with a cold background plasma, whose density is much higher than the beam density, can be described in the framework of the theory of linear perturbations [10]. Modeling using the PIC method showed that the electronic component is well described in the hydrodynamic approximation by the equations for the electron fluid: the continuity equation and the force balance equation.

A full mathematical description of intense beams is difficult, since the real flow consists of many moving particles, it is almost impossible to take into account the interaction between them. Often some simplifying assumptions are introduced. For example, in the L–code program, which is widely used to study the properties of relativistic beams [11–13], the macroparticles are used. In the present work, an attempt was made to simulate the process of free expansion of the spherical–shaped bunch based on molecular dynamics simulation.

## 2. Results and discussion

### 2.1. Results

Figure 1 shows a schematic illustration of the ion beam in INURA setup. The ion beam is transported without a focusing magnetic field, i.e. by ballistic mean. As can be seen from this figure, the use of the ballistic compression method complicated the geometry. During beam generation, it is neutralized due to various passive electron sources: from the diode cathode, during bombardment of structural elements of the cathode by beam ions, ionization of the residual gas in the chamber, etc. Under such neutralization conditions, i.e. without additional electron sources, the beam values shown in table 1 are achieved. Additional ferroelectric plasma sources are supposed to be placed in the expansion region of the pipe, i.e. to the focus of compression.



**Figure 1.** Schematic representation of the ion beam in INURA installation.

**Table 1.** Parameters of the ion beam in INURA installation.

Parameter	Value
Amplitude of Accelerating Voltage	400kV
Acceleration voltage pulse duration	70 ÷ 100ns
Ion beam current (amplitude value)	10kA
Ion beam composition	Protons+carbon ions (70/30)
Anode diameter (diameter of the annular beam at the generation stage)	20cm
Beam diameter in focus	Up to 5cm
Ion density in focus	10 <sup>9</sup> ÷ 10 <sup>12</sup> cm <sup>-3</sup>
Beam ion temperature	1 ÷ 2eV

Table 1 gives the amplitude value of the ion current  $I_{am} = I\sqrt{2}$ . If we consider the ion beam as a cylinder with a diameter  $d$  and charge density  $\rho = n_i e$  then

$$V_D = \frac{I}{\pi(d/2)^2(n_i e)}, \quad (1)$$

when  $n_i = 0.3 \cdot 10^{10} \text{ cm}^{-3}$  and  $d = 5 \text{ cm}$  directional velocity is estimated as  $V_D = 0.3 \cdot 10^8 \text{ m/sec}$ . According to the installation scheme, the focal length is equal  $F = 15 \text{ cm}$ , then the time required for bunch to travel the focal length is estimated as  $t_D = 5 \cdot 10^{-9} \text{ sec}$ .

To study the evolution of the ion bunch under plasma neutralization, we used the method of molecular dynamics. In this method, it is important to know the interaction potentials of the particles of the system [14–16]. The interaction of ions is described on the basis of the Coulomb potential in the case when the influence of plasma electrons is not taken into account. In the case of neutralization of the bulk positive charge of the bunch by electrons appearing in the channel from special sources, the interaction potential of ions in the bunch becomes screened, leading to a decrease in repulsion between ions. The screened Coulomb potential is referred to in the literature as the Debye–Hückel potential (or the Yukawa potential):

$$\Phi(r) = \frac{Q^2}{4\pi\epsilon_0} \frac{\exp(-r/\lambda_{D_e})}{r}, \quad (2)$$

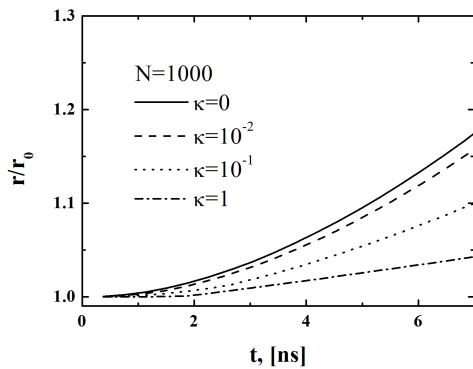
here

$$\lambda_{D_e} = \left( k_B T_e / (4\pi e^2 n_e) \right)^{1/2}, \quad (3)$$

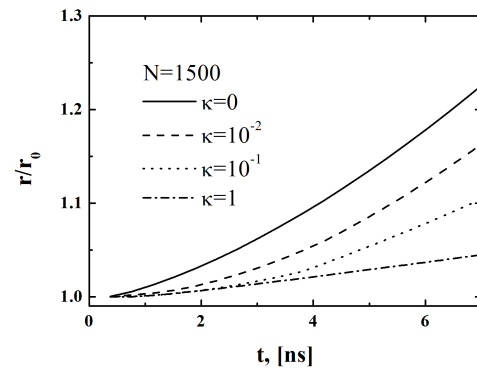
is the electron Debye screening length [17–21],  $Q$  is the ion charge. In this work the following dimensionless parameter was used: the screening parameter  $\kappa = a/\lambda_{D_e}$ , where the average distance between ions is  $a = (3/4\pi n_i)^{1/3}$  and  $n_i$  is the numerical density of the ions. The aim of our study was to examine the effect of plasma neutralization on the size of the ion bunch using the molecular dynamics method. We simulate the pulsed beam, which is for simplicity a spherical bunch. At the start of the simulation, the ions are distributed inside the bunch according to a random distribution, the thermal velocities of the ions are also randomly distributed. The equations of motion of bunch particles, which interact with each other on the basis of the Yukawa potential, are solved. At the initial stage of modeling, the size of the bunch is kept constant until Maxwellization of the velocities is reached. After that the boundary condition is

not supported. Particles can go beyond the initial boundaries of the bunch, allowing the bunch to spatially expand.

The simulation results with number of ions in bunch  $N = 1000$  and  $N = 1500$  are shown in figure 2 and figure 3, correspondingly. Here, the dependencies of the ratio of the expanding bunch's radius to the initial one are shown, as functions of the time after Maxwellization. The solid line corresponds to the bunch without plasma neutralization. The remaining curves were obtained for different values of screening parameter  $\kappa$ . It is shown that with an increase of  $\kappa$ , the growth of the bunch is suppressed more strongly and when approaching the value of  $\kappa = 1$ , the size of the bunch changes only slightly during the observed time. In the absence of beam neutralization, the bunch expands to almost 10% of its original size by time  $t_D = 5 \cdot 10^{-9}$  sec, while with a screening parameter  $\kappa = 1$  it is less than 3%. Condition  $\kappa = 1$  can be reached with  $n_e \sim [(T_e[eV])^{1/2}(10^{13} \div 10^{16})] \text{ cm}^{-3}$  at  $n_i \sim 10^{10} \div 10^{12} \text{ cm}^{-3}$ .



**Figure 2.** Time dependence of the reduced bunch radius for different values of  $\kappa$ ,  $N = 1000$ .



**Figure 3.** Time dependence of the reduced bunch radius for different values of  $\kappa$ ,  $N = 1500$ .

In figure 4, curves are plotted for the reduced bunch radius as a function of the number of ions  $N$ , obtained at time  $t = 6 \cdot 10^{-9}$  sec. The dependences demonstrate the increase in the bunch radius with growth of the ion number in the bunch. It is consequence of the increase in the spatial charge. But for properly neutralized bunch ( $\kappa = 1$ ) its expanding is not so crucial and can even be prevented.

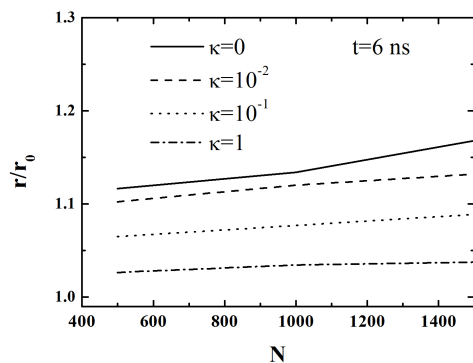
Based on some simplifications the equation (4) was obtained that describes the expansion of a beam of charged particles, which is valid for both positively and negatively charged particles [22] :

$$\frac{d^2 R}{dZ^2} = \frac{1}{2R}, \quad (4)$$

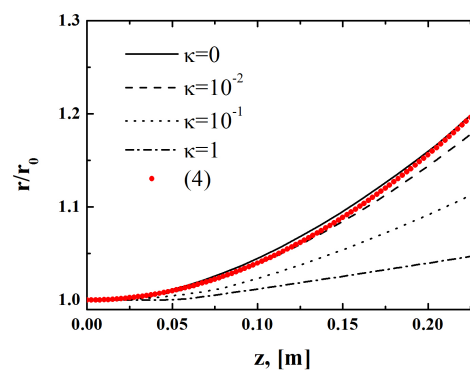
$R = r(z)/r_0$ ,  $Z = \left\{ -\frac{I}{2\pi\epsilon_0(-2Q(u-u_0)^3/m_i)^{1/2}} \right\}^{1/2} z/r_0$ ,  $z$  is longitudinal coordinate. The initial conditions for equation (4):  $R(0) = 1$  and  $R'(0) = 0$ . The second condition means that the beam was not initially expanded. Figure 5 shows the simulation results for different values of screening parameter and calculations by formula (4) for the reduced beam radius depending on the longitudinal coordinate  $z$ .

## 2.2. Discussion

In the present work, we tried to describe the expansion of the spherical bunch of the pulsed ion beam generated in the INURA setup. The results showed that with good neutralization of the spatial charge, the beam can hold the initial transverse size for a time sufficient to reach



**Figure 4.** Reduced bunch radius at a fixed time  $t = 6 \cdot 10^{-9}$  sec as a function of the particle number in the bunch.



**Figure 5.** Reduced bunch radius as a function of the longitudinal coordinate,  $N = 1000$ .

the target. It was shown that at  $\kappa = 1$  the bunch does not expand more than 3% and reduced radius of the bunch at fixed time weakly depends on the number of particles in the bunch. On the basis of our investigation we can give estimation for required parameters of plasma; minimal electron numerical density is  $n_e \sim [(T_e[eV])^{1/2}(10^{13} \div 10^{16})] cm^{-3}$  at  $n_i \sim 10^{10} \div 10^{12} cm^{-3}$ .

Results were compared with the calculations by the equation (4) for an expanding beam of charged particles without plasma neutralization. A certain agreement between results of equation (4) and simulation data at  $\kappa = 0$  is seen.

### 3. Conclusions

Based on the results obtained, the following conclusion can be made that to prevent unwanted expansion of the ion beam in the INURA installation, a complete neutralization of the space charge is necessary. More detailed studies of this issue will be done in future works.

### Acknowledgments

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