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FEATURES OF THE PICKUP DIAGNOSTIC AT LOW ENERGY IN THE COOLER OF NICA BOOSTER

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Abstract

This work deals with an experimental study of changes in the amplitude of the sum signal induced at pickup stations, which can be associated with the formation of space charge waves arising along the electron beam. In the case of low electron energies, the space charge of the beam can have a significant effect on the interpretation of the obtained experimental data.

INTRODUCTION

The electron cooling system of the NICA booster is designed to accumulate an ion beam during injection and to cool it after acceleration to a certain intermediate energy. This system was developed and tested at the BINP SB RAS [1]. The maximum electron beam energy in it is 50 keV, which corresponds to an ion energy of 100 MeV / nucleon. The minimum energy of 1.74 keV corresponds to the injection energy. The schematic design of the electron cooler is shown in Fig. 1 and the main specification at the Table 1.

The electron beam is generated by an electron gun immersed into the longitudinal magnetic field. After that the electron beam is accelerated, moves in the toroid magnet to the cooling section where it will interact with ions of Booster storage ring. After interaction the electron beam is decelerated and absorbed in the collector. The centrifugal force in toroid magnets is compensated by the electrostatic plates.

Table 1: Main Specifications of the Cooler.

ions type	from p+ up to $^{197}Au^{31+}$
electron energy, E	1,5 ÷ 50 keV
electron beam current, I	0.2 ÷ 1.0 Amp.
energy stability, $\Delta E/E$	$\leq 1\cdot 10^{-5}$
electron current stability, $\Delta I/I$	$\leq 1\cdot 10^{-4}$
electron current losses, $\delta I/I$	less than $3\cdot 10^{-5}$
longitudinal magnetic field	0.1 ÷ 0.2 T
inhomogeneity of the field	
in the cooling section, $\Delta B/B$	$\leq 3\cdot 10^{-5}$
transverse electron temperature	≤ 0.3 eV
ion orbit correction:	
residual gas pressure	10^{-11} mbar.

For the effective realization of the electron cooling method, it is necessary to accurate combine both beams inside cooling section. For this purpose, electrostatic sensors or pickup electrodes are used. For position measurements the ion beam must be bunched using the RF system of booster. In order to measure the position of the electron beam, it is modulated with sinusoidal voltage at 3 MHz with amplitude 10 V applied to the control electrode. The magnitude of the electron current modulation is usually much less than the total current of the electron beam. In order to get additional information about the dynamics of the electron beam a system of 4 pickups located along its trajectory is used.

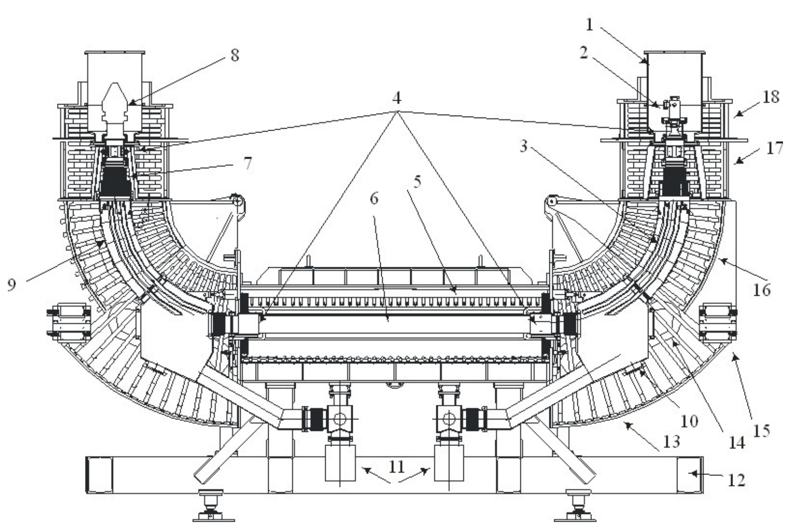

Figure 1: Design of electron cooler for NICA booster. The SF_6 vessel is 1, the electron gun is 2, the electrostatic plate is 3, pickups are 4, cooling section is 5, the vacuum chamber of cooling section is 6, NEG pump is 7, collector is 8, the vacuum chamber of toroid is 9, titanium pump is 10, the ion pumps are 11, the support is 12, the toroid is 13, the correction coil is 14, the corrector of ion beam is 15, the toroid solenoid is 16, the matching solenoid is 17, the gun solenoid is 18.

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At a electron energy of 5 kV and electron current 50 mA the value of sum signal along trajectory was close to constant for different pickups. But with a small value of the electron beam energy of 1.74 kV, a strong decrease in the magnitude of the signals at the far from the gun pickup electrodes was observed (see Fig. 2). At a current of 400 mA, a minimum signal value is observed at the 3-rd pickup electrode and a strong increase almost to the initial value is observed at the 4-th pickup electrode. The most probable cause of this phenomenon may be the propagation of space charge wave along the electron beam with the formation of a standing wave.

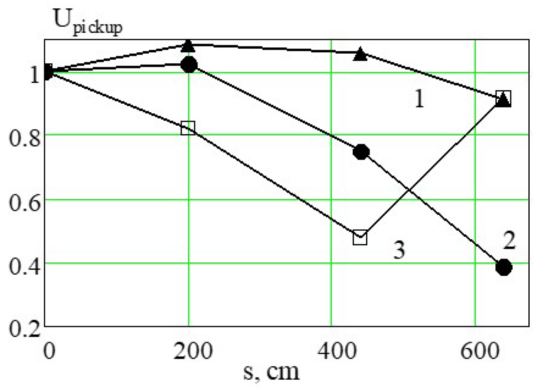

Figure 2: Normalized values of the sum signal along the electron beam trajectory at different electron beam currents: 42mA (1), 167 mA (2), 440 mA (3). The signal is normalized to the amplitude of the signal in the first pickup station. The electron energy is 1.74 keV. For relative calibration between different pickup stations, signal amplitudes were used at an electron energy of 5 keV, when spatial charge waves can be neglected.

AXIAL SYMMETRIC OSCILLATION

At small density of the electron beam the wave-vector of oscillation is $k_s = \omega/u_0$ and the length of wave $\lambda_s = 2\pi/k_s \approx 800$ cm is much larger than electron beam radius. In this case, it is possible to use the long-wave approximation of the longitudinal field. At the same time, it is assumed that the charge density varies slightly along the beam, so one can locally use the approximation of a constant linear density to find the radial electric field.

The exact solution of the linearized equations of hydrodynamics in a longitudinal magnetic field and the Poisson equation is described in [2-5]. The continuity equation, the equation of motion and the Poisson equation can be written as

$$\frac{\partial n'}{\partial t} + div\left(n_0\vec{v'}\right) + \vec{v}_0\nabla n' = 0$$

$$m_e\left(\frac{\partial\vec{v'}}{\partial t} + (\vec{v}_0\nabla)\vec{v'}\right) = e\vec{E} + \frac{e}{c}\left[\vec{v'}\times\vec{B}_0\right],$$

$$\Delta\varphi = -4\pi e n',$$

where the velocity $\vec{v}_0$ takes into account the presence of the azimuthal velocity of electron drift. Using Fourier series expansion for oscillations of space charge potential

$$\delta\phi(r,\theta,s,t) = \sum_{l=-\infty}^{\infty}\sum_{k_s=-\infty}^{\infty}\delta\phi_l(r,k_s)\exp[i(l\theta + k_s s - \omega t)]$$

allows to write Poisson equation as

$$\frac{1}{r}\frac{\partial}{\partial r}r\frac{\partial}{\partial r}\delta\phi_l - \frac{l^2}{r^2}\delta\phi_l + T^2\delta\phi_l = 0,\ 0 < r < a_e \quad (1)$$

$$\frac{1}{r}\frac{\partial}{\partial r}r\frac{\partial}{\partial r}\delta\phi_l - \frac{l^2}{r^2}\delta\phi_l - k^2\delta\phi_l = 0,\ a_e < r < b. \quad (2)$$

Here

$$T^2 = k_s^2\frac{\dfrac{\omega_p^2}{(\omega - k_s u_0 - l\omega_0)^2} - 1}{1 - \dfrac{\omega_p^2}{\nu^2}}$$

$$\nu^2 = (\omega - k_s u_0 - l\omega_0)^2 - (\Omega + 2\omega_0)^2,$$

$\Omega = eB/(m_e c)$ is cyclotron frequency, ω_0 is angular velocity of the equilibrium rotation of the electron column as a whole

$$\omega_0 = -\frac{\Omega}{2}\left[1 - \left(1 - 2\frac{\omega_p^2}{\Omega^2}\right)^{1/2}\right].$$

In the region $0 < r < a_e$ Eq. (1) has a solution in the form of

$$\delta\phi_l = AJ_l(Tr), \quad (3)$$

where J_l is a Bessel function of the first kind of order l, remaining finite at $r = 0$ and A is some constant. A similar solution in the outer region Eq. (2) of the electron beam can be written as

$$\delta\phi_l = B\cdot I_l(k_s r) + C\cdot K_l(k_s r) \quad (4)$$

where the functions K_l and I_l are modified Bessel functions of the first and second kind and B, C are some constants. From the boundary conditions on the surface of the conducting vacuum chamber and on the surface of the beam, it is possible to obtain the dispersion equation in the form [4]

$$k_s a_e\frac{K_l(k_s b)I'_l(k_s a_e) - K'_l(k_s a_e)I_l(k_s b)}{K_l(k_s b)I_l(k_s a_e) - K_l(k_s a_e)I_l(k_s b)} - \\ -\left(1 - \frac{\omega_p^2}{\nu^2}\right)Ta_e\frac{J'_l(Ta_e)}{J_l(Ta_e)} = l\frac{\omega_p^2(\Omega + 2\omega_0)}{\nu^2(\omega - k_s u_0 - l\omega_0)}. \quad (5)$$

The strokes of the Bessel functions in the equation mean their derivative with respect to the full argument. In an extremely strong magnetic field Eq. (5) can be written

$$k_s a_e\frac{K_l(k_s b)I'_l(k_s a_e) - K'_l(k_s a_e)I_l(k_s b)}{K_l(k_s b)I_l(k_s a_e) - K_l(k_s a_e)I_l(k_s b)} - Ta_e\frac{J'_l(Ta_e)}{J_l(Ta_e)} = 0. \quad (6)$$

If one consider the azimuthally symmetric case $l = 0$ and use the approximation of long waves

$$k_s b,\ k_s a_e \ll 1,\ a_e = 1\ cm,\ b = 7.5\ cm,$$

one can expand the Bessel functions in the vicinity of zero argument and simplify both terms of Eq. 6

$$k_s a_e\frac{K_l(k_s b)I'_l(k_s a_e) - K'_l(k_s a_e)I_l(k_s b)}{K_l(k_s b)I_l(k_s a_e) - K_l(k_s a_e)I_l(k_s b)} \approx -\frac{1}{\ln(b/a_e)},$$

$$\frac{1}{\ln(b/a_e)} - Ta_e\frac{J_1(Ta_e)}{J_0(Ta_e)} = 0,\ \ T^2 = k_s^2\frac{\omega_p^2}{(\omega - k_s u_0)^2}. \quad (7)$$

Eq. (7) allows to obtain a solution in both cases for homogeneous and inhomogeneous distribution of space charge fluctuation over the beam cross-section. To do this, one need to find several solutions to this transcendental equation and make the required linear combination from the corresponding perturbation density distributions. In order to find the roots of Eq. 7 it is sufficient to construct the

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intersection of the graphs of the functions included in the equation.

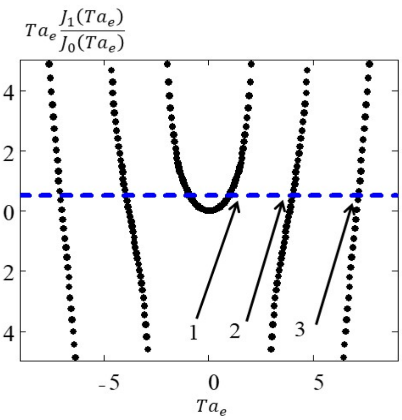

Figure 3: Graphical solution of Eq. 7. Point 1 corresponds to the main radial mode μ_0=0.95, points 2 and 3 correspond to additional solutions of this equation μ_1 and μ_2.

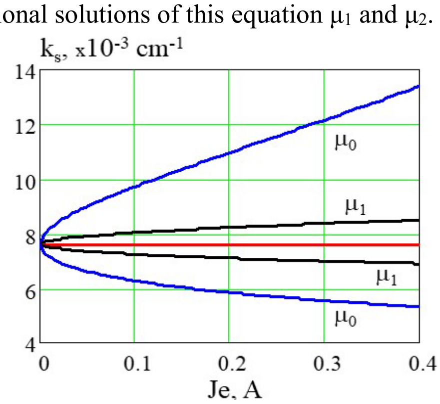

Figure 4: Dependence of the longitudinal component of the wave vector of the wave propagating along and opposite of the flow k_+ and k_- versus the beam current. The curves correspond to the values for the main μ_0=0.95 and the first radial mode with μ_1=3.97. Straight line (red colour) corresponds to the "dispersion equation" of particles without taking into account the space charge $k_s=\omega/u_0$.

The dispersion equation corresponding Eq. (7) can be written in the form

$$(\omega - k_s u_0)^2 = \frac{1}{\mu_i^2} k_s^2 a_e^2 \omega_p^2 \tag{8}$$

Figure 4 shows the longitudinal wave vector dependences on the beam current estimated by Eq. (8).

The difference of dispersion equation for k_+ and k_- wave leads to the evolution of the amplitude of the sum signal along the beam trajectory. Assuming that after the control electrode, the electron density is

$$n'_i(r,t) = \delta n_{i0} f_i(r) \cos(\omega t),$$

then the electron density is

$$n'_i(r,t) = $$
$$= \frac{1}{2}\delta n_{i0} f_i(r)[\cos(\omega t - k_+ s) + \cos(\omega t - k_- s)]$$

at s distance from the place of excitation.

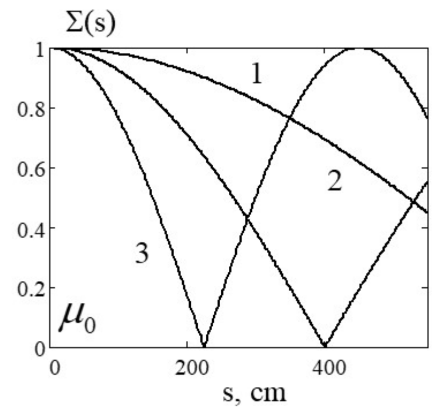

Figure 5: Longitudinal distribution of the amplitude of the sum signal Σ(s) for azimuthally symmetric modes μ_0.

Figure 5 shows the amplitude of pickup signal for the main azimuthally symmetric mode μ_0. In the case of a radially inhomogeneous beam density distribution, the contribution of the mode μ_1 is not very large. The graphs are calculated for different values of the total electron beam current of 50 (1), 150 (2) and 300 (3) mA. In order to calculate the initial electron density n_0, it is taken into account that the energy of the electrons in the beam will differ from the voltage at the cathode by the amount of the "drawdown" potential

$$\Delta\phi = \frac{2J_e}{\beta c}\ln\left(\frac{b}{a_e}\right)$$

caused by the space charge of the electron beam.

One can see that the qualitative behavior of the signals distribution in Figures 2 and 5 is quite similar, so the mechanism described above may explains the observed effect.

CONCLUSION

Electrostatic pickups are one of the main methods for obtaining information about the properties of an electron beam in electron cooling devices. The analysis presented in the article shows that the propagation of spatial charge waves in a sufficiently intense beam should be taken into account when analysing experimental data.

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