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USING OF PICOSECOND HIGHCURRENT RELATIVISTIC ELECTRON BEAMS FOR FORMING OF ROTATING ELECTRON RINGS

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Recently the progress in generation of powerful picoseconds beams takes place. It's presented in the paper of G.A. Mesyts & M.I. Yalandin (Physics-Uspekhi, V.175 № 3, pp.225-246, 2005). Such beams have attractive characteristics:

1 – High density of the emission current
2 – High values of pulse currents (kiloamperes)
3 – High electron energies (hundreds-thousands keV)
4 – High repetition rate (kilohertzes)
5 – Possibility of application in forevacuum conditions

For example, parameters of the RADAN setup are: Voltage U=150-200 kV, Pulse duration T_{imp}=0,2-4 ns, Repetition rate f=1-100 Hz, Beam energy E=200-300 keV, Beam current I=1-2,5 kA, Beam duration T_b=0,2-1,5 ns.

The tubular rotating electron beams which are formed in such setups can be used for different applications, including researches in collective ion acceleration.

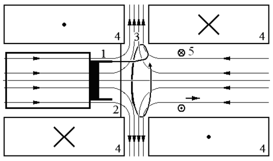


Fig.1. Forming of electron ring in a cusp-type magnetic field: 1-Cathode; 2-Anode; 3-Cusp region; 4-Solenoids; 5-Compressed electron ring.

One of the ways to form the electron rings is electron beam going through the static magnetic field of special geometry (cusp), which can be realize in space between two opposite connected solenoids.

The principal scheme of this process is illustrated on Fig.1. The electron beam from the cathode 1 is coming in a cusp region 3 which is formed by solenoids 4. Magnetic flux in this region is radial, and before the cusp the field is axial and reversing after cusp. After cusp the tubular electron beam 5 is formed and the density of electrons in the beam is growing up.

Electron rings forming have been investigated in a different works. The results of such researches are presented in the table:

	R, cm	I_d, kA	I_b, kA	B, kG	U, MV	E, MeV	T^d_{FWHM}, ns	T^b_{FWHM}, ns	N_e	T_{trap}, μs
1970 Cornell	0,35–0,65	10	—	3–10	~ 0,5	—	50	—	10^{14}	—
1973 Cornell	3,5	20	10–20	0,53	—	0,35	—	—	—	9,5
1975 Maryland	6	4–20	2–10	~ 1,4	1–3	2–3	20	—	—	0,1–0,2
1978 Maryland	6	30	≤ 2	1,5	—	2,3	30	2	$\sim 10^{12}$	~0,1
1979 Maryland	6	—	1,5	1,6	—	2,5	—	3–5	$5\cdot 10^{11}$	~0,1

The main parameters of the experimental setups for the forming of tubular rings
R - Cathode radius; I_d - Diode current; I_b - Beam current after cusp; B - Magnetic field in the homogeneity region; U – Diode voltage; E – Injected electron energy; T^d_{FWHM} – pulse duration of diode voltage at half maximum of the signal; T^b_{FWHM} – beam duration after cusp; Ne – number of trapped electrons; T_{trap} – time of electron confinement in the trap.

In this paper we investigated a forming of a tubular electron beam by the particle-in-cell method with the one-particle approximation without the space charge effects. We are calculating the electron beam dynamics in a static magnetic field in a cylindrical coordinate system using a Runge-Kutt or modified Euler methods.

The equations of electrons motion in axial symmetrical magnetic field are:

$$\begin{cases} \ddot{r} = r\dot{\varphi} + \dfrac{e}{mc\gamma} r\dot{\varphi}B_z \\ \ddot{z} = -\dfrac{e}{mc\gamma} r\dot{\varphi}B_r \end{cases}$$

where

$$\dot{\varphi} = -\frac{e}{mc\gamma}\left[rA_\varphi - \left(rA_\varphi\right)_0\right]\frac{1}{r^2}$$

The magnetic field is calculated using "Poisson Superfish" application package. It allows to calculate the necessary magnetic fields in axial symmetrical coordinate system with the consideration the magnetic saturation effects.

Error in magnetic field calculations is average ~ 10^{-4} %, and for beam dynamics is ~0,12 % in homogeneous field region and ~ 1,4 % in the cusp region.

The results of the magnetic field calculating are shown on the fig.2 and fig.3.

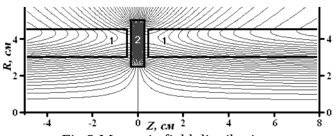


Fig.2 Magnetic field distribution.
1 - solenoids; 2 - Magnetic field thickener (Iron).

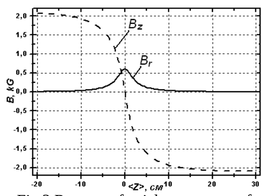


Fig.3 Reverse of axial component of magnetic field B_z and radial component of magnetic field B_r on the radius R = 2 cm.

The magnetic system parameters are: Solenoids length – 1 m; Inner and outer diameters of solenoids – 6 and 9 cm; Current density in the solenoids – 1,1 kA/cm^2; Field thickeners width – 6 mm; Inner and outer diameters of field thickener – 5 and 10 cm; Magnetic field in homogeneous region – 2,1 kG. As evident from fig.3, the cusps width on half maximum of magnetic field is ~ 4 cm.

Presented results have been obtained by simulation of 10000 particles with uniform initial distribution of the beams density. Pulse duration – 100 ps (RMS σ_z=0,78 cm); Radius of annular cathode R_0 = 2,25 cm; Electrons energy E_0 = 1 MeV.

For estimate the results we have look on the next parameters: <Z> – coordinate of the center of inertial of the ring; β_Z – longitudinal velocity of the ring; β_φ – speed of azimuthally rotation of the ring; σ_z – RMS of the rings length in axial direction; N/N_0 – the ratio of the number of particles in a range $\langle Z\rangle \pm 3\sigma_z$ to initial number of particles; $\lambda=(N/\sigma)/(N_0/\sigma_0)$ – longitudinal density of the ring.

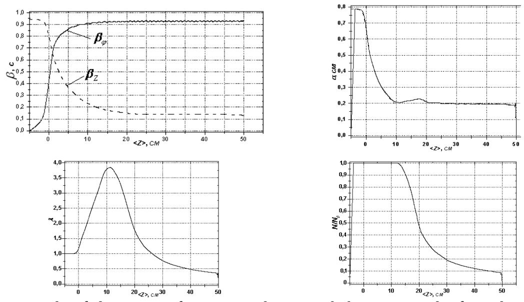


Fig.4. Results of electron ring forming simulations with the next spreads of initial parameters: tube thickness – ΔR= 100 µs; relative energy spread $\delta E=\Delta E/E_0$ = 0; output angel half-spread $\Delta\alpha$=0.

As evident, selected parameters are ensured decelerating of an axial motion β_Z in 8 times, and the axial velocity β_φ is growing up to the initial electrons speed. At the position of <Z> = ~11cm, the density λ exiting the initial at 4 times, what is according to compressing of axial dimension σ_z of the ring from 0,8 to 0,2 cm.

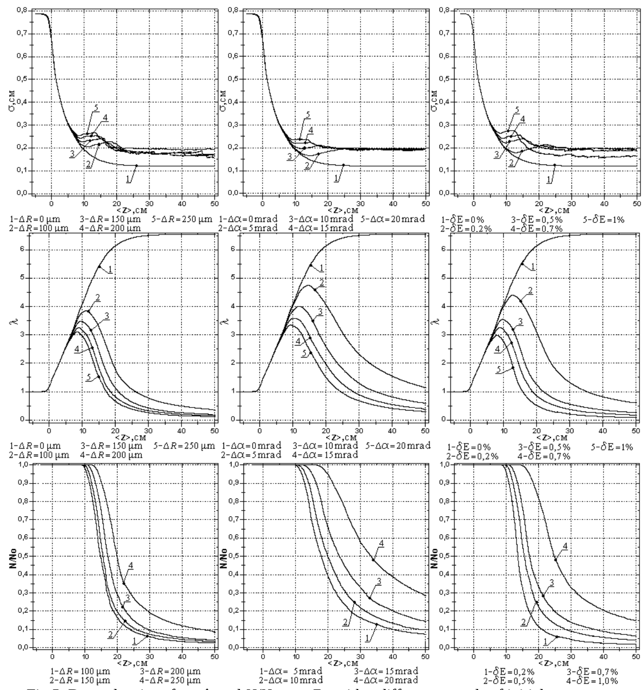
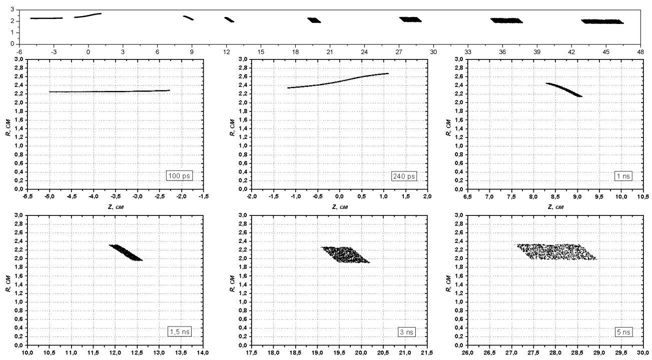


Fig.5. Dependencies of σ_z , λ, and N/N_0 on <Z> with a different spreads of initial parameters.



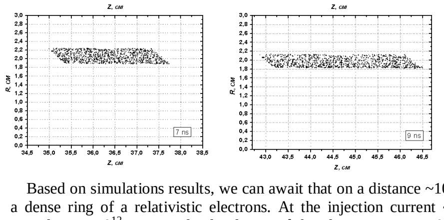


Fig.6. Ring sections in R-Z plane in a different time instants.

Based on simulations results, we can await that on a distance ~10 cm from the cusp it's formed a dense ring of a relativistic electrons. At the injection current ~2 kA number of the trapped particles is ~10^{12}. Longitudinal velocity of the electron ring is ~0,2 c with the small size of the ring ~2 mm. Such parameters of the ring are allowed to consider it for different applications. For using the ring for collective ion acceleration it's necessary to decelerating of axial velocity of the ring to ~0,1 c, ensure the focusing of the electrons with consideration of the space-charge forces with the loading of ions in the ring. Rely on the experience of the previous experiments, their problems can be solved by the using of resistive walls or using a low vacuum mode (fluid jets) for electron ring decelerating by the trapped ions, which are moreover produced the focusing of electrons in the ring.

Future plans: development of the methods of simulations including the calculating the self electrical and magnetic fields of the ring; simulations with the resistive walls; modeling of loading the ions in the ring.