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LINEAR INDUCTION ACCELERATOR LIA-2 UPGRADE

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Abstract

X-ray facilities based on a linear induction accelerator are designed to study of high density objects. It requires the high-current electron beam to obtain a small spot and bright x-ray source using a conversion target. The electrons source in such facilities is injectors capable generate pulses with a duration from tens of nanoseconds to several microseconds and a current of several kA. The transportation and focusing of high-current beams into diameter about 1 mm is difficult due to the space charge phenomena. In the similar induction accelerators (AIRIX [1], DARHT [2], FXR, etc.), auto-emission cathodes are used to obtain high-current electron beams. The use of a thermionic cathode, in compared to auto-emission cathode, provides stable generation of several pulses with a time interval of several microseconds, but makes high requirements on the injector vacuum system: not less than 10^{-7} Torr [3].

Dispenser Cathode

The cathode assembly is an integral part of any beam source system. Elements of the cathode assembly, such as a heater or internal components, not formally effects on the beam dynamics. However, the uniformity of heating of the cathode surface, is very important for the uniformity of emission. To develop of this issue, the thermal calculations of cathode heating system were performed in order to optimize the cathode assembly. In particular, the homogeneity of the temperature distribution along the surface of cathode core was studied. This is important for high quality beam forming.

3D-modeling was performed using COMSOL Multiphysics software platform. In simulation of heat exchange by radiation between solids in vacuum the module "Surface-to-surface radiation" was used. A 3D-model of the cathode assembly was used as the initial geometry. All calculations were made for a stationary thermal conditions. The appearance of the modified cathode assembly is shown in Fig. 1.

At power 2500 W, the heater temperature reaches 1500 °C, the cathode surface temperature is about 1000 °C. The asymmetrical shape of the heater (Fig. 2) leads to an increase in the local zone by 4 degrees, which is an acceptable value (Fig. 3).

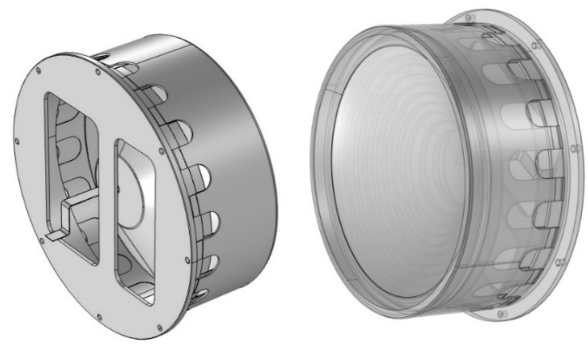

Figure 1: The cathode assembly.

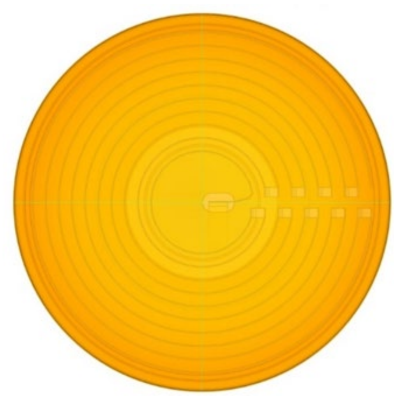

Figure 2: The cathode model for simulate heating process in COMSOL to estimate the temperature distribution along the surface.

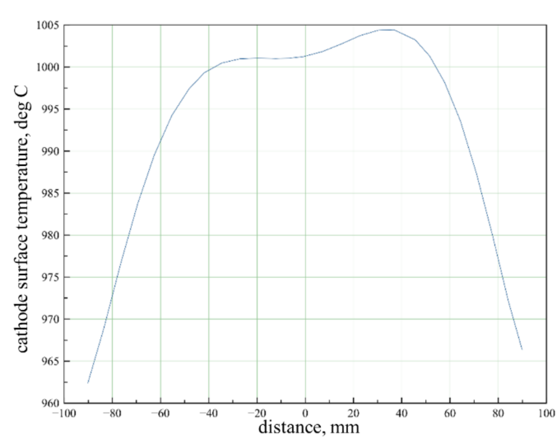

Figure 3: Cathode surface temperature distribution in horizontal section.

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Dispenser Cathode in Double-Pulse Mode

Generation of two pulses with a short time interval using the dispenser cathode is not difficult, because there is no plasma in the cathode region after the first pulse. As shown in Fig. 4, both current pulses have approximately the same shape and the first pulse does not effect on the second. The time interval between pulses is 4 µs.

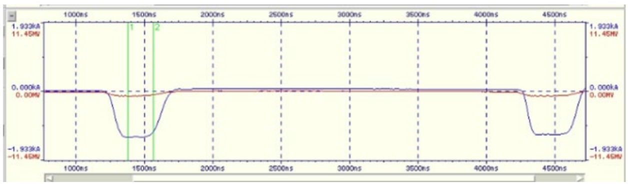

Figure 4: Double-pulse mode at 1.5 MeV, current is 1.25 kA, time delay is 4 µs.

Beam Dynamics Simulation

Currently, few different codes have been developed to simulate high-current electron beams in accelerator. To correctly take into account the space charge, it is necessary to simulate with a large number of macroparticles, while the computation time is long, even when using high-performance computing technologies. A simple alternative for simulation with macroparticles can be a code based on the envelope equation for an axially symmetric beam with the uniform distribution. This "K-V envelope code" was developed at the BINP SB RAS.

For simulation of the beam dynamic in LIA-2 the REDPIC [4] code and the K-V envelope code were used. The equation of motion with space charge is:

$$r'' + k_s r - \frac{P}{r} - \frac{\epsilon^2}{r^3} = 0.$$

Here we consider a round beam with a radius r and the uniform distribution of space charge density, $P = \frac{2I}{I_a \beta^3 \gamma^3}$ is the generalized beam perveance, $I_a = 17$ кA, ϵ is the beam emittance, $k_s = (\frac{eB_z}{2mc\beta\gamma})^2$ is the rigidity of solenoidal lenses, β is the particle velocity and γ is the Lorentz factor.

In Fig. 5 the comparison of simulations using the K-V envelope codes (black dotted line) and REDPIC (blue filling) is shown. Simulation in the REDPIC program was carried out with uniform transverse distribution and pulse duration is about 200 ns. The character time of solving with such parameters is about 4 hours. In the K-V envelope code (dashed line), it takes a few seconds to integrate the envelope equation with longitudinal step about 1mm. The results of simulations by different codes demonstrate a good agreement.

The LIA-2 magnetic system consists of three pulse shielded solenoids, with length 217 mm and maximal field up to 2 kG, and final focusing solenoidal lens with length 60 mm and maximal field 4.5 kG. The main task of magnetic system is beam transportation from the cathode to the target assembly without current losses and high-quality focusing.

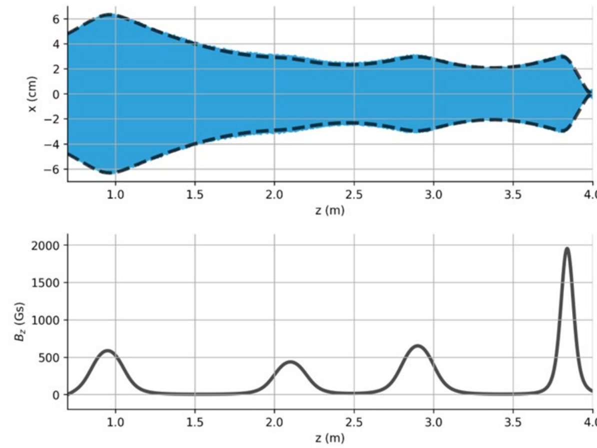

Figure 5: A comparison of simulations using the K-V envelope code (black dotted line) and REDPIC (blue filling). The bottom line shows the longitudinal distribution of magnetic field.

The spherical aberration in final focusing lens doesn't allow to focus large-diameter beam at the entrance of lens to the required size of 1 mm. Spherical aberration leads to the fact that particles with different distance from lens axis have different focusing length (Fig. 6).

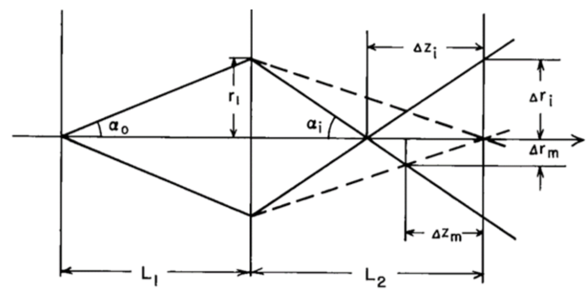

Figure 6: Schematic representation of particle trajectories when passing through a thin lens with spherical aberration.

For achieving of spot size less than 1 mm the beam size at the entrance to the final focusing lens with aberration was estimated. Consider the final focusing lens with following parameters in Table 1.

Table 1: Final Focusing Lens Specifications

Parameters	
Length	60 mm
Aperture radius	60 mm
Magnetic fields	Up to 4 kG

The results of simulation with UltraSAM code for parallel round beam without space charge for different beam radius are presented at Fig. 7. Table 2 shows the values of Δr_{min} depending on the beam size r_a at the lens entrance, obtained analytically and using simulation in the UltraSAM program.

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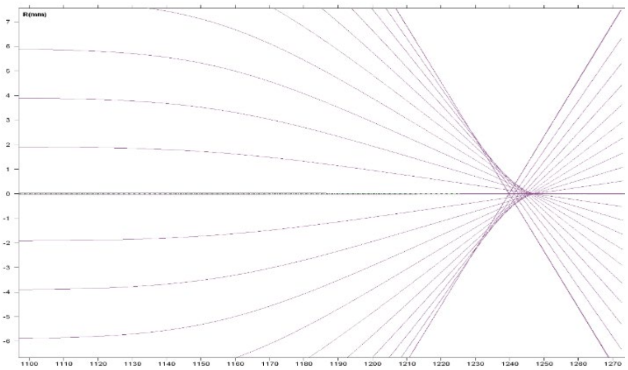

Figure 7: Simulation of the beam trajectories at final focusing lens.

Table 2: Comparison Results

r_a, mm	UltraSAM $\Delta r_{min}, mm$	Analytical calc. $\Delta r_{min}, mm$
25	0.88	0.71
20	0.41	0.35
15	0.19	0.16
10	0.05	0.04

The difference between the simulation results and the analytical estimation is within 20%, which can be explained with errors in numerical simulations of small beam size in the crossover. Nevertheless, it can be concluded that beam radius r_a should be not above 20 mm at the entrance of final focusing lens.

LIA-2 Magnetic System Optimization

For avoiding of the effect of spherical aberration in final focusing lens on the focal spot size the beam size at the lens entrance should be adjusted. The installation of additional solenoidal lens before the final lens is the possible solutions of this problem (Fig. 8).

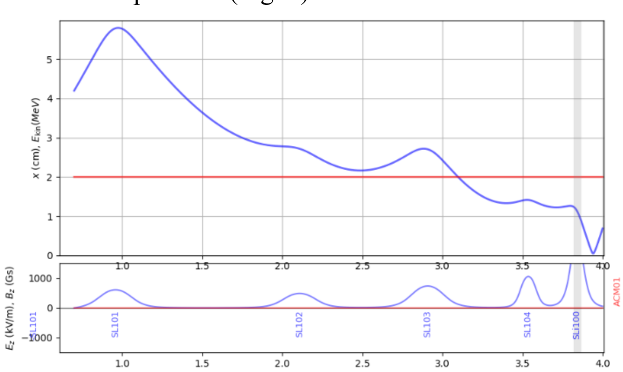

Figure 8: Resulting envelope and magnetic field longitudinal distribution.

Simulation with K-V envelope code shows that additional lens allows varying the beam size at final focusing lens entrance in the wide range and allows satisfying the requirement for beam size described above.

New Design for Diagnostics and Vacuum Chamber before Conversion Target

An upgraded version of the beam transfer channel has been developed, including a new current transformer, a transient radiation sensor for measuring the transverse beam profile, and an additional lens between the third and final lenses (Fig. 9).

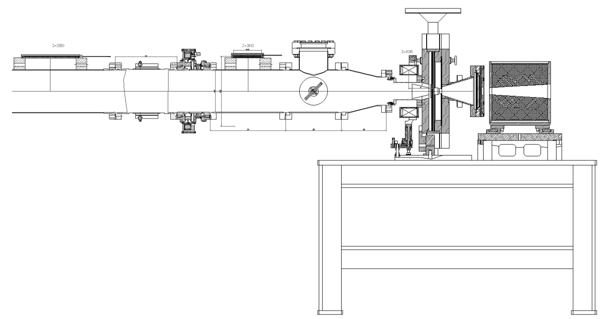

Figure 9: New version of the beam transfer channel.

It allows to visually observe the transverse profile and size of beam, measure the main beam parameters, reduce influence of spherical aberration, and simplify the adjustment of magnetic system for the beam focusing in the conversion target.

CONCLUSION

New version of cathode was manufactured and successfully installed in the LIA-2.

"K-V envelope code" has been developed that allows in a few seconds to simulate the beam envelope with space charge phenomena and spherical aberration of the final lens.

The new transport channel with additional diagnostic elements with aperture 152 mm was proposed for measuring of transverse profile and other beam parameters.

ACKNOWLEDGEMENTS

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