Investigation of the possibility of modeling the thermal effect of plasma on the Tokamak divertor using a frequency-pulse electron beam

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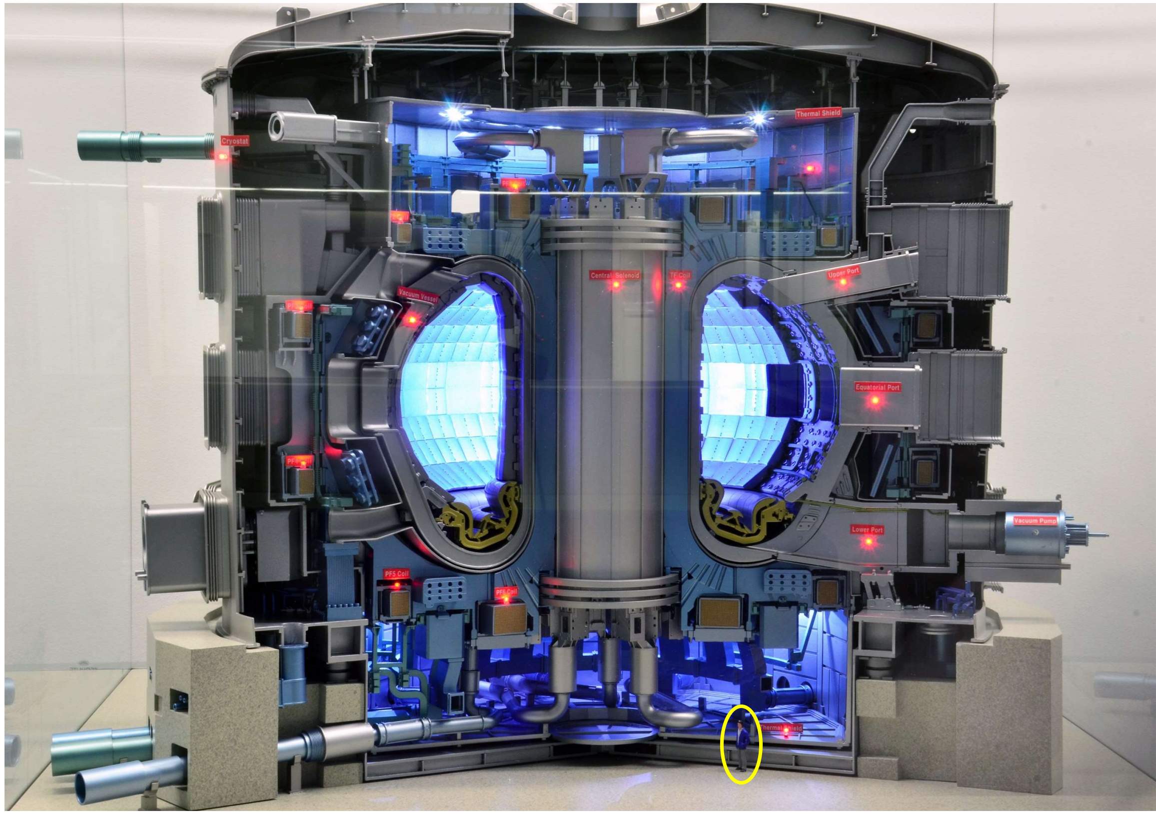
Motivation

Thermonuclear fusion → ITER International Tokamak → Tokamak diverter

- Intense pulsed thermal loads arising as a result of fast transient processes in the hot plasma of the tokamak - disruptions of the plasma column and periodic instabilities of the peripheral plasma (ELM I);
- In ITER, according to estimates, thermal loads (ELM I) reach ~ 0.6 MJ/m^2 with a process duration of ~1 ms with a frequency of ~10 Hz with a plasma lifetime of hundreds of seconds in one working pulse;
- The number of such events over the entire life cycle of the ITER over $\sim 10^8$;



ITER Tokamak

Simulation of thermal loads using electron beam

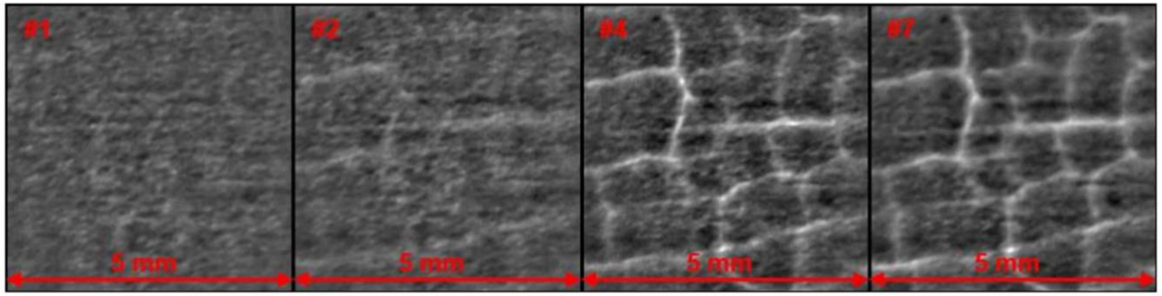
Irradiation of a tungsten surface with an electron beam with particle energies in the range of tens of keV.

<u>Some stands in the world:</u>

<u>JUDITH 2(Germany);BETA(Russia, Novosibirsk)</u>

JUDITH 2 (Germany): Number of pulses reached on target $\leq 10^5$

BETA (Russia, Novosibirsk): Number of pulses reached on target $\leq 10^3$, up to 10 Gw/m^2



Goal of the work

Studying the possibility of modeling pulse-periodic thermal loads on the surface of tungsten in a long-term mode using an electron beam generated in a gun with a thermionic cathode.

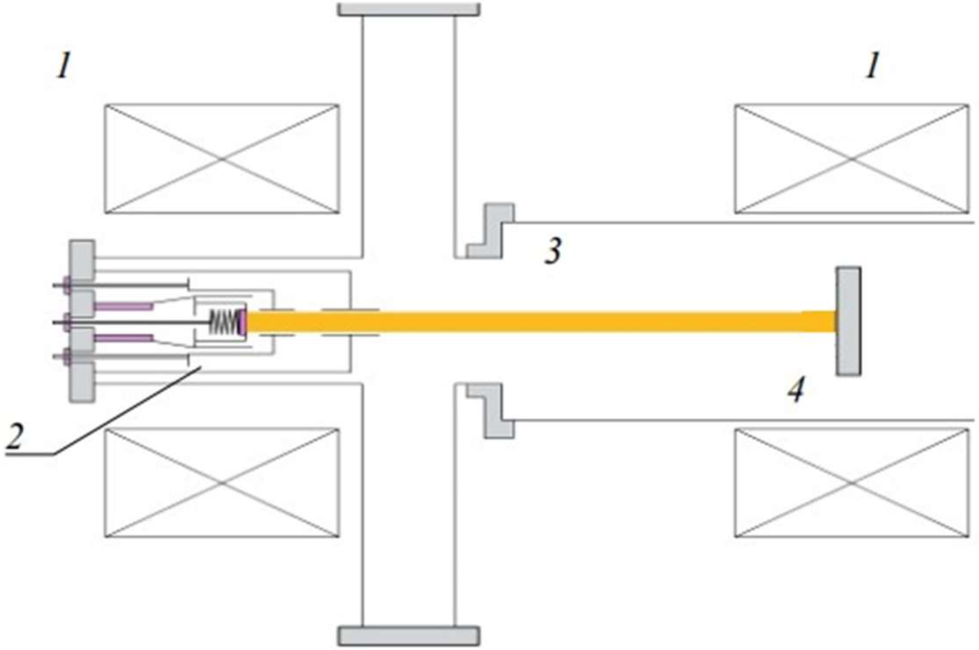
- Exposure load ~ 100 J/cm^2 with a pulse duration of about 1 ms on the surface of a tungsten target over an area of about 1 cm^2 at a frequency of 10−20 Hz.
- Total number of pulses per target up to 10^7.
- Direct geometry design, where the beam is transported to the target at a distance of ~0.5 m from the cathode in a direct driving magnetic field created by two external coils.

Stages of work :

1. **Selection of electron beam parameters and cathode design.**
2. **Modeling and numerical calculation of the beam source.**
3. **Experimental study of the correspondence of the calculated parameters of the gun to the real ones, and debugging of the operation of the filament power supply systems and the formation of pulsed accelerating voltage, vacuum and magnetic systems.**
4. Study of the stability of the beam source in the pulse-frequency mode.
5. Study of cathode durability.

Electron beam source

Electron gun operating in a magnetic field has been developed.



Schematic diagram of stand : 1 – magnetic field coils;
2 – electron gun with a thermal cathode;
3 – vacuum chamber (the pumping system is not shown);
4 – target

Specificity :

- The gun allows to use almost the entire range of cathode units developed at the BINP SB RAS (LaB_6, Ir_5Ce).
- The choice of the concept with a magnetized beam is due to the ease of controlling the beam size on the target and, therefore, the exposure energy density.

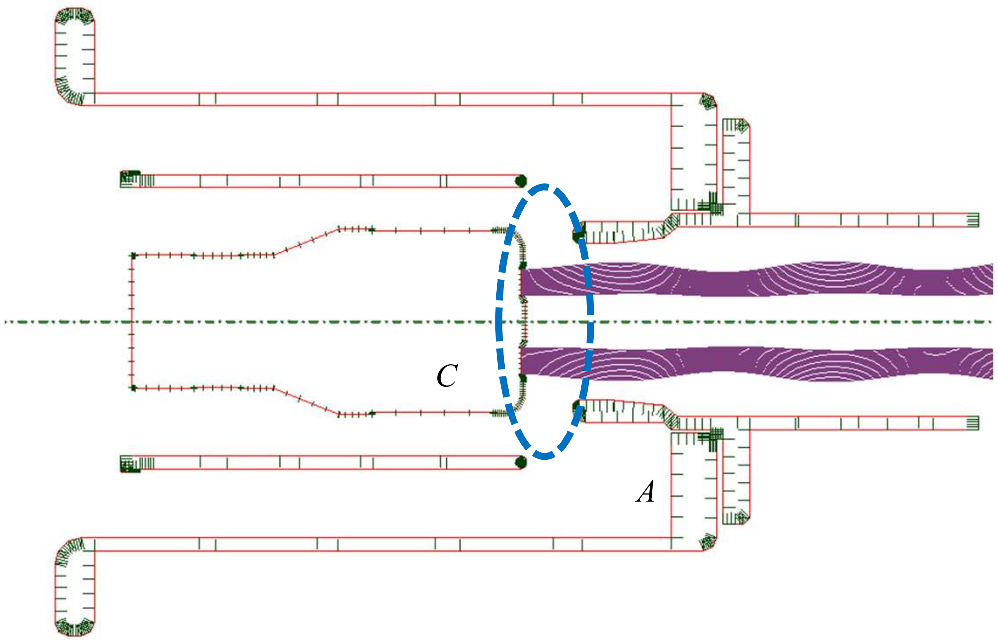
$$\left(\frac{r}{r_c}\right)^2 = \frac{B_c}{B}$$

Numerical modeling of an electron beam source

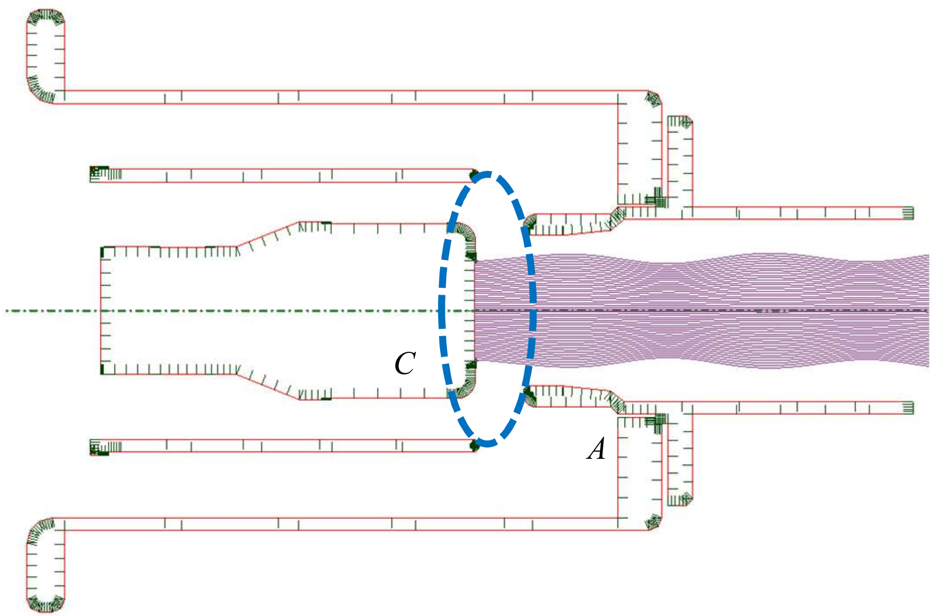
Using the UltraSAM software package, numerical calculations were carried out in the mode of limiting the current density by space charge:

- Electron beam envelope in the transport path
- Current density profile on the target

1) Cathode with a ring-shaped emitting surface



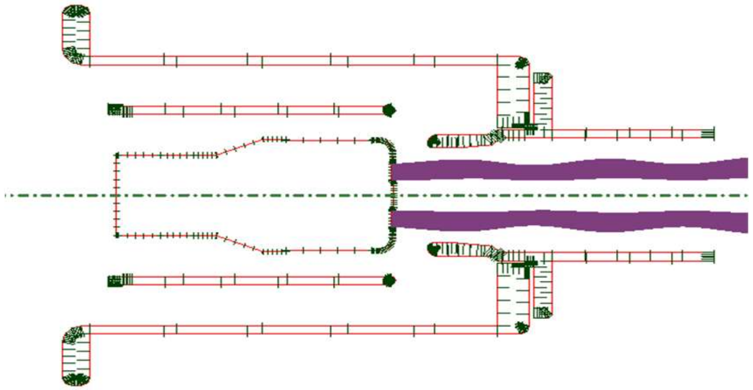
2) Cathode with a circular emitting surface

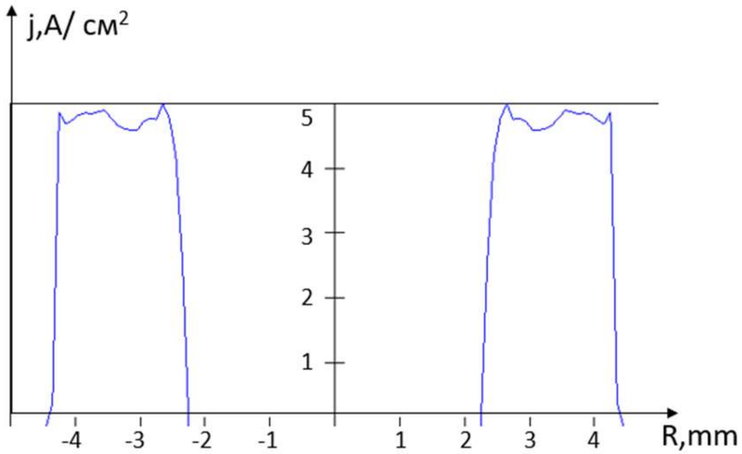


Cathode with a ring-shaped emitting region

Calculation parameters:

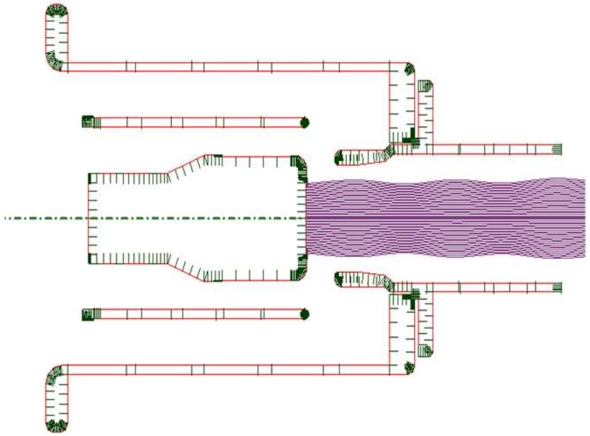
- U=15 kV
- l~0.5 m
- B = 85.5 mT

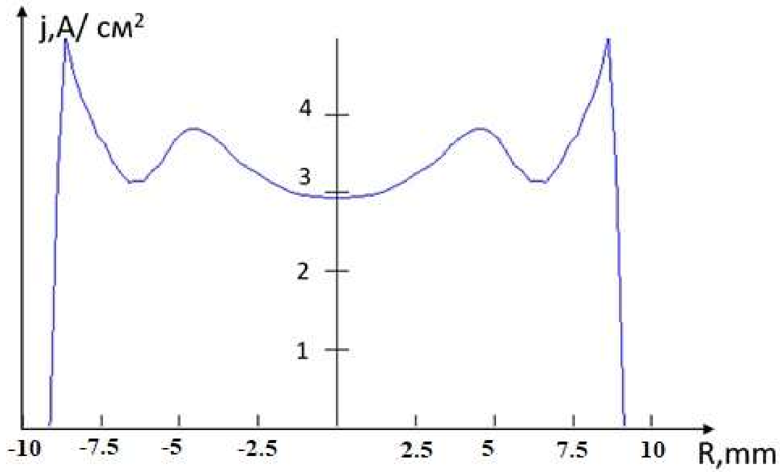




Results :

- With U=17kV, j=6.46 A/cm², electron beam energy density ~ 100 J/cm².
- Calculated perveance $4.54 * 10^{-6}$.





Results :

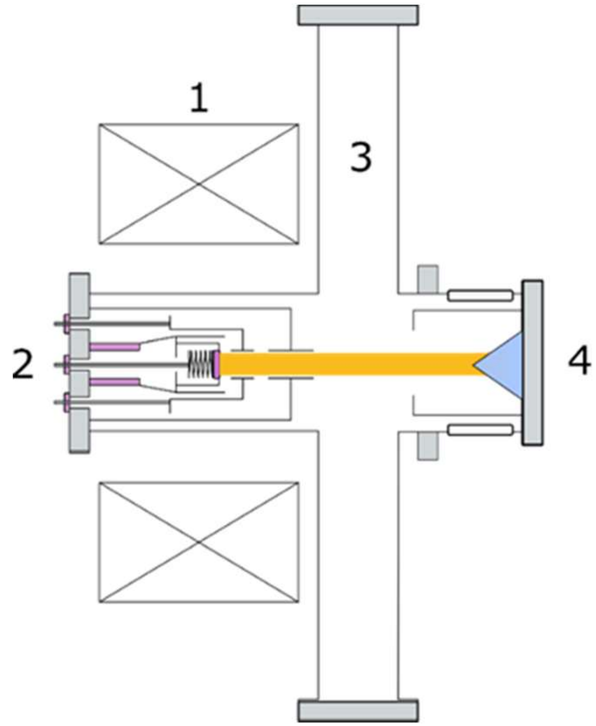
- Strong unevenness in Current density profile , With U=18kV, j=6.4 A/cm ², electron beam energy density ~ 100 J/ cm ².
- Calculated perveance $5.30 * 10^{-6}$.

Experimental stand of the first stage

The tasks of the stand of the first stage included:

- Checking the agree of the calculated parameters of the gun to the real ones;
- Debugging the power systems, formation of pulsed accelerating voltage, vacuum and magnetic systems;
- Initial beam diagnosis;

The beam is transported in a vacuum chamber to a target at a distance of ~0.5 m in an axially symmetric magnetic field created by a single coil.



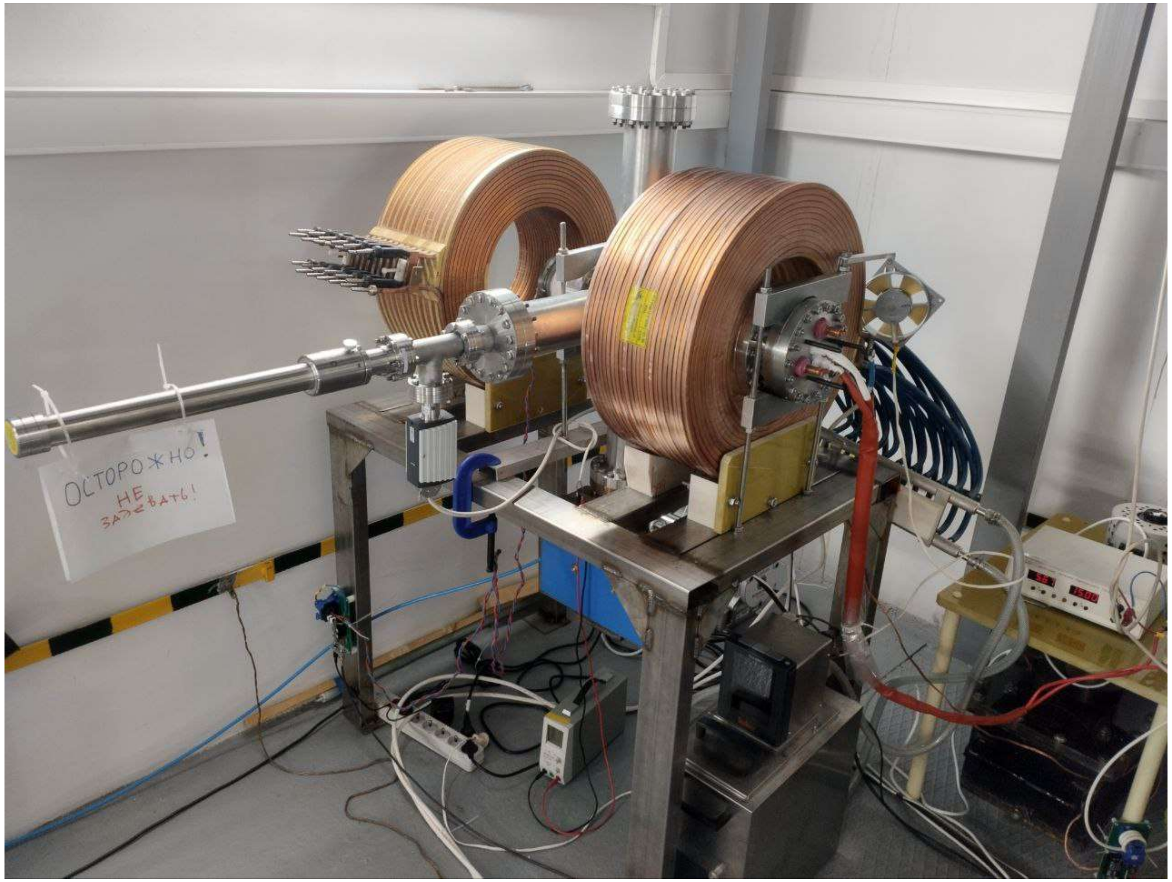
1 – magnetic field coil;
2 – electron gun with a thermal cathode;
3 – vacuum chamber;
4 – Faraday cylinder;

Experimental stand of the first stage

The main components of the stand are:

- magnetic system;
- vacuum chamber with pumping means;
- electron gun with a thermionic cathode;
- gun and magnetic field power systems;

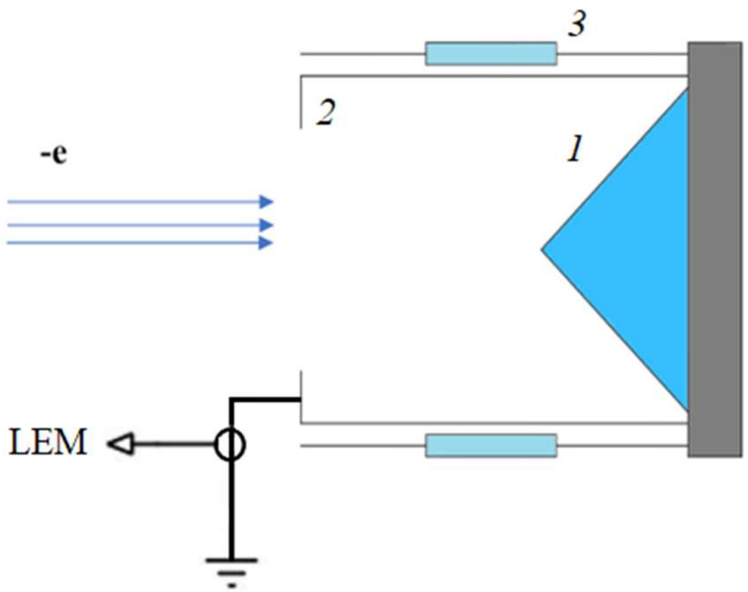
system for recording current and accelerating voltage signals;

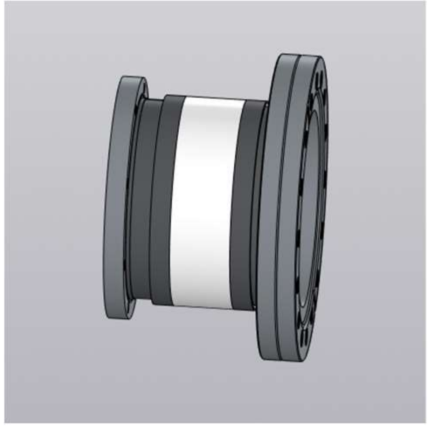


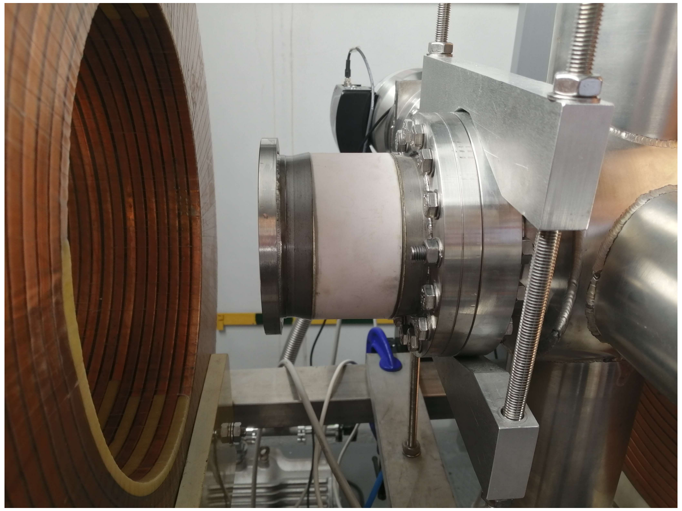
Beam collector :

Faraday Cup

- Beam current measurements.



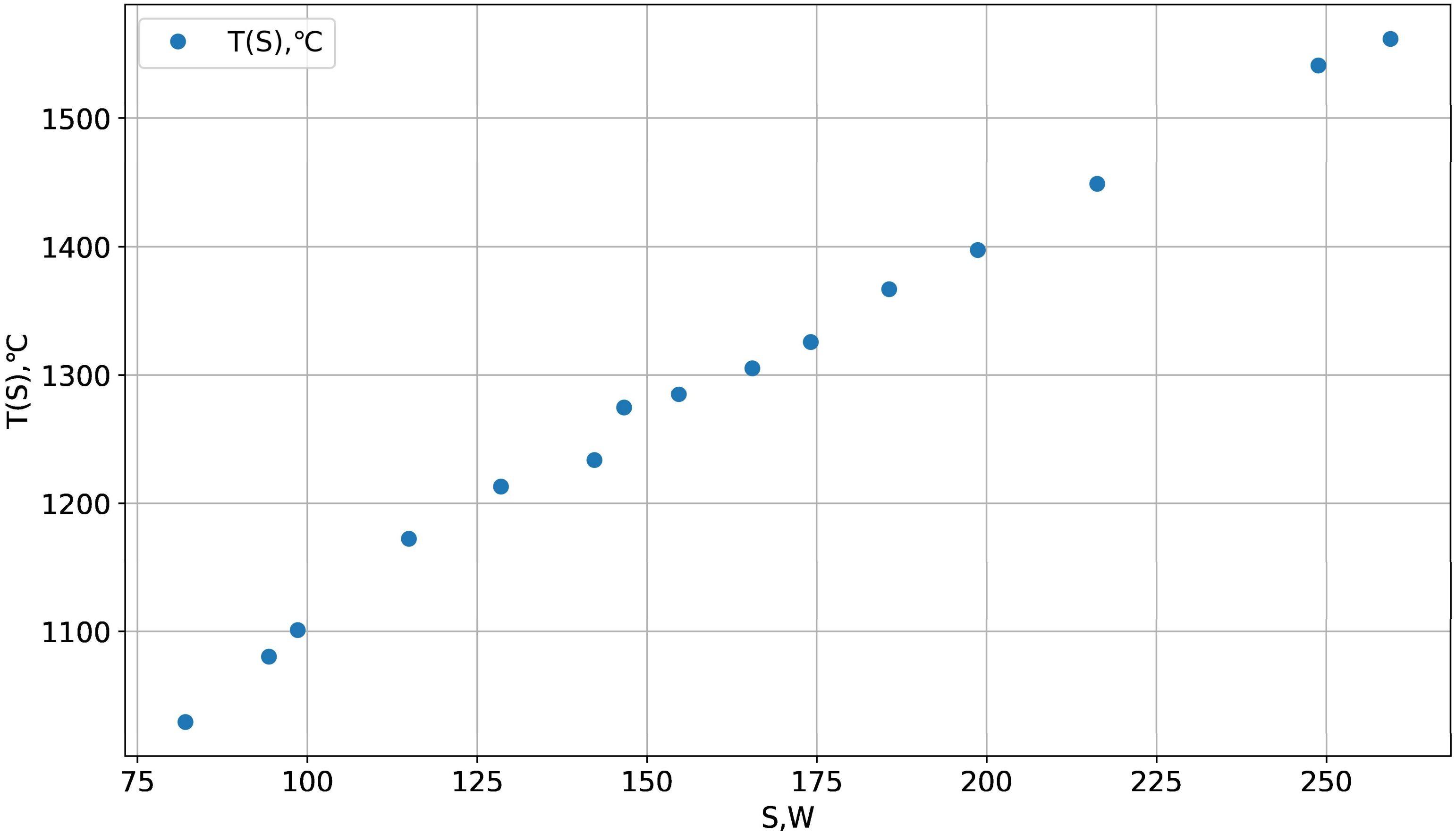




1- molybdenum cone; 2- ceramic insulator; 3-conducting cylinder (Nichrome)

Preparation for experimentation

The LaB_6 ring cathode was tested on a separate vacuum stand. The dependence of the surface temperature on the power supplied to the heating element of the cathode was measured using a pyrometer.



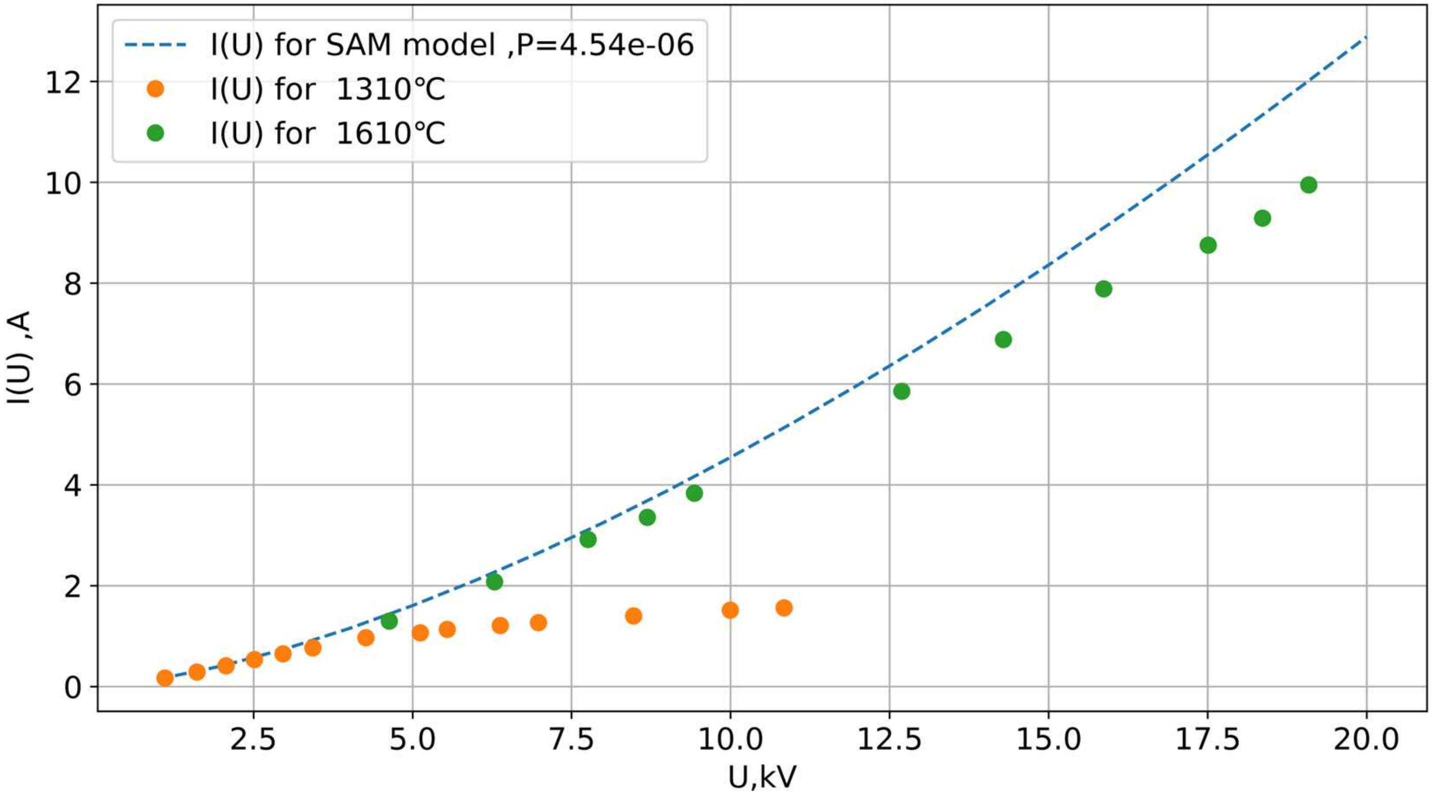
Experimental conditions

The first experiments with an electron beam were carried out under the following conditions:

- Ring-shaped cathode $S = 1.5\ cm^2$
- One coil to provide magnetic field
- vacuum$\approx 1 * 10^{-7}\ Pa$
- Cathode heating temperature $1310\ C^{\circ} - 1610\ C^{\circ}$
- Accelerating voltage up to $U = 19\ kV$
- Pulse duration from 200 µs to 2 ms
- Maximum value of leading magnetic field B_{max}~80 mT

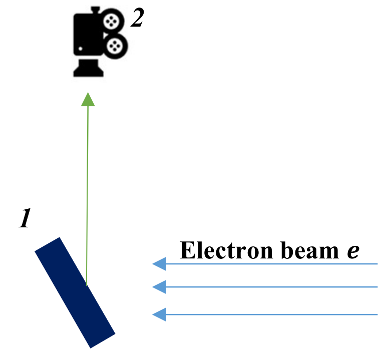
Experimental results

Current-voltage characteristics of the LaB_6 cathode, with a ring-shaped emitting region, at the cathode heating temperature 1310 °C and 1610°C.



- Beam current of 10 A was achieved at a voltage at the cathode of about 19 kV, which means the beam power density on the target is ~ 1.27 GW/m^2, which obviously satisfies the requirements of materials science problems.

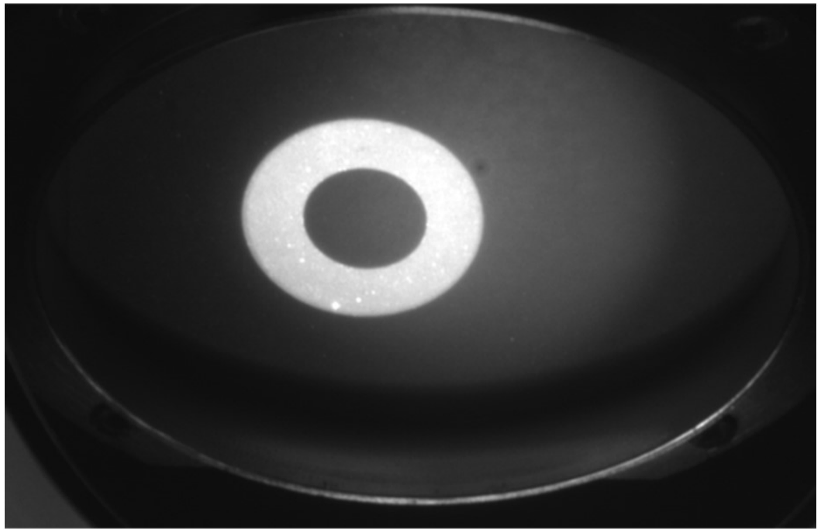
Diagnostic parts of the stand:



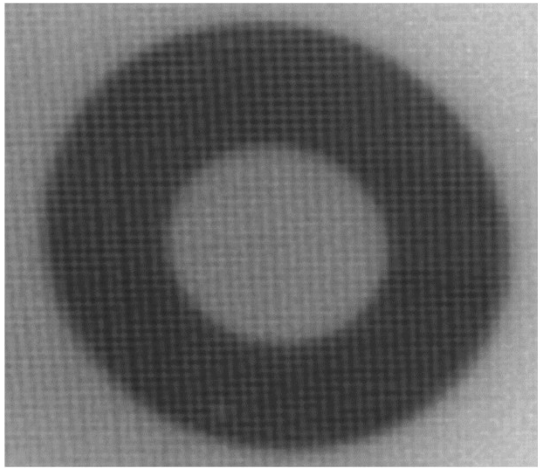
1–Collector (Ceramics), 2 - CCD camera

Allows you to obtain a picture of the current density distribution on the target.

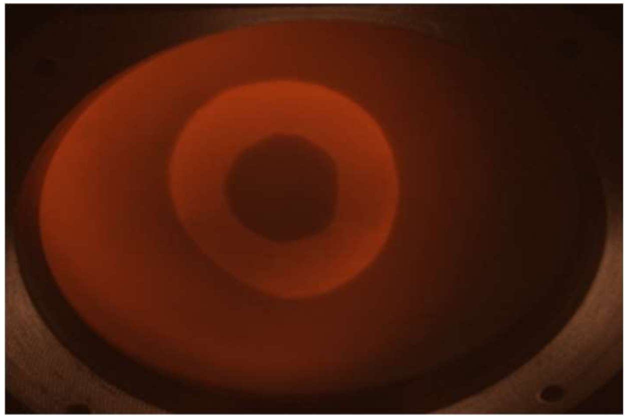
- Use of ceramics (Al_2O_3: Cr -“chromax”)
- An option with silver plating is being considered



Ceramics with chromium coating 20 nm



Ceramics with metal mesh (mesh pitch 1mm)



Ceramics (Al_2O_3: Cr-«chromax»)

Results of work and future plans

Results :

1) 2-D beam modeling, numerical calculations: electron beam envelope in the transport path, current density profile on the target.
2) The dependence of the surface temperature on the power supplied to the cathode heating element was obtained.
3) The first stage stand was built, on which the first experiments on generating and measuring the characteristics of an electron beam.
4) At an accelerating voltage of 19 kV, a beam current of about 10 A was obtained, which certainly satisfies the requirements of the materials science problem.

Nearest plans:

- ❑**Completion of the creation of the experimental stand;**
- ❑**Diagnostics of beam current density distribution on the target;**
- ❑**Creation of a cooled target (Tungsten) and study of cathode durability**
- ❑**Study of the stability of source characteristics during long-term performance ($\geq 10^6$ impulses);**

THANK YOU FOR ATTENTION !