RZLINE MHD model of Z-pinch discharge based EUV source

Vladimir Ivanov, Vladimir Novikov*, Anna Solomyannaya*, Vladimir Krivtsun and Konstantin Koshelev

Institute of Spectroscopy RAS (ISAN), Troitsk, Russia, e-mail: vladimirivanov@isan.troitsk.ru

***Keldysh Institute of Applied Mathematics RAS, Moscow, Russia, novikov@kiam.ru**

We report a new two-dimensional (r, z) Euler MHD code RZLINE for modeling EUV sources. The code have standard set of features like: shock waves propagation, electron and ion thermo-conductivity, pinch effect, magnetic field diffusion etc. Opacity effects are included by using effective total escape parameter ξ technique using THERMOS-BEELINE code (see poster of V.Novikov et all "Calculation of Xe an Sn emission spectra in discharge devices: the influence of reabsorption in spectral lines.

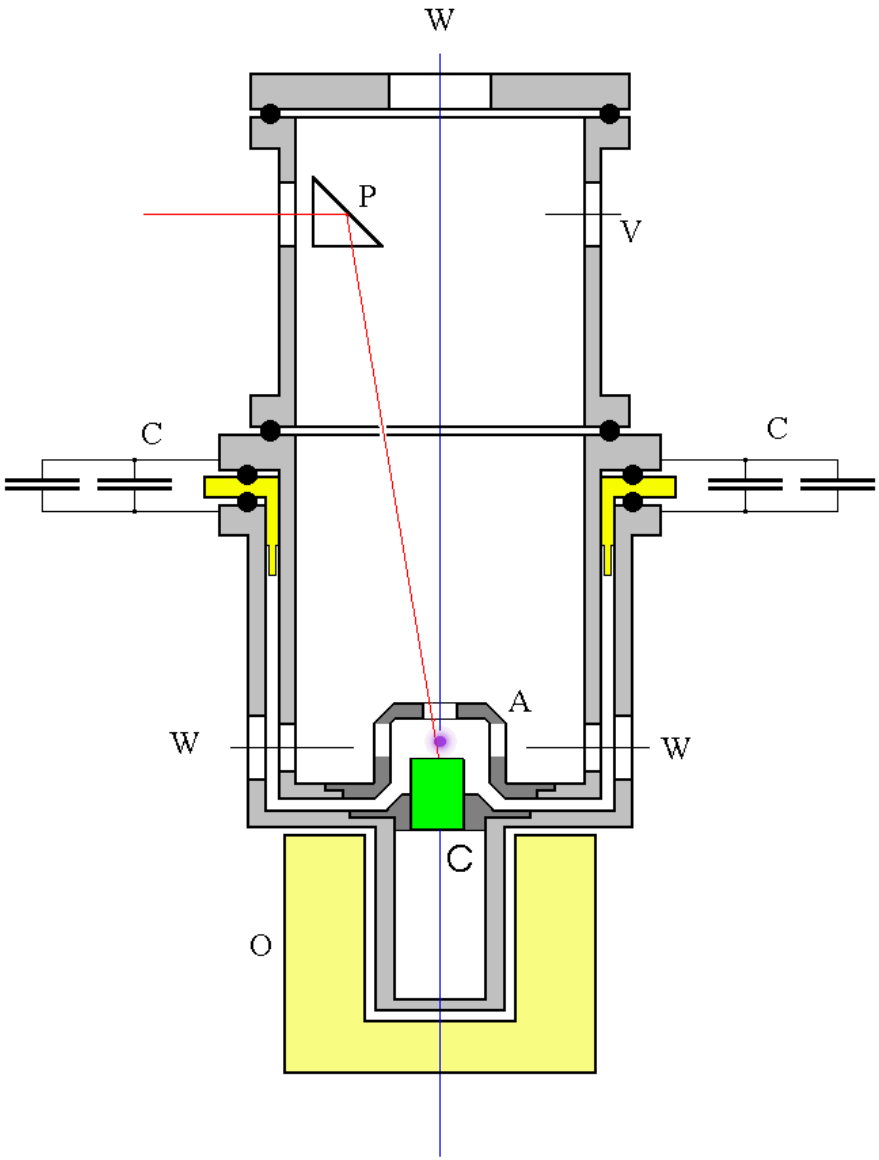
Main new features of RZLINE code

1. Low density gap near anode is essential part of a discharge, which is responsible for high resistance of the discharge at initial stage as well as heating of anode material. For the adequate description of this region several processes have been included: non Spitzer conductivity, non stationary ionization dynamics and transfer of energy by electron current
2. Another new feature of the code is the model of initiating phase of discharge which includes laser ablation of plasma by short laser pulse (temperature profile in liquid tin is calculated as well) with subsequent expansion of tin plasma.
3. Model of evaporation of anode surface, which provides particles into discharge region and provides shortcutting of the discharge.
4. Opacity effects are included by using effective total escape parameter ξ technique using THERMOS-BEELINE code (see poster of V.Novikov)

Radiative properties of plasma.

- Modern discharge EUV sources are based on radiative collapse of Z-pinch in tin plasma (e.g.ISAN, Philips, TRINITY). About 80% of battery energy in these discharges are converted to thermal one; half of which is then radiated from the plasma. Radiative phenomena play extremely important role in the energy balance of plasma.
- EUV lithography uses very narrow 2 % band near 13.5 nm, therefore radiating lines position should be known with high precision.
- To calculate radiative phenomena we used newly developed code THERMOS-BEELINE which makes possible self-consistent calculation of level kinetics and radiation transport for different plasma geometrical configurations. The code includes:
  - radiation transport of overlapped spectral lines at arbitrary optical thickness and using realistic line profiles;
  - verified atomic database for low-Z materials (H, He, O) and also for Xe, Sn and their mixtures. It is possible to get EUV spectra in the range 80-250 A.

Benchmarking object - ISAN tin discharge based EUV source



W – windows C – capacitor O - oven

P – prism A - anode

V – valve C - porous tungsten cathode with liquid tin inside

U = 2-5 kV

C = 0.2-0.8 μF

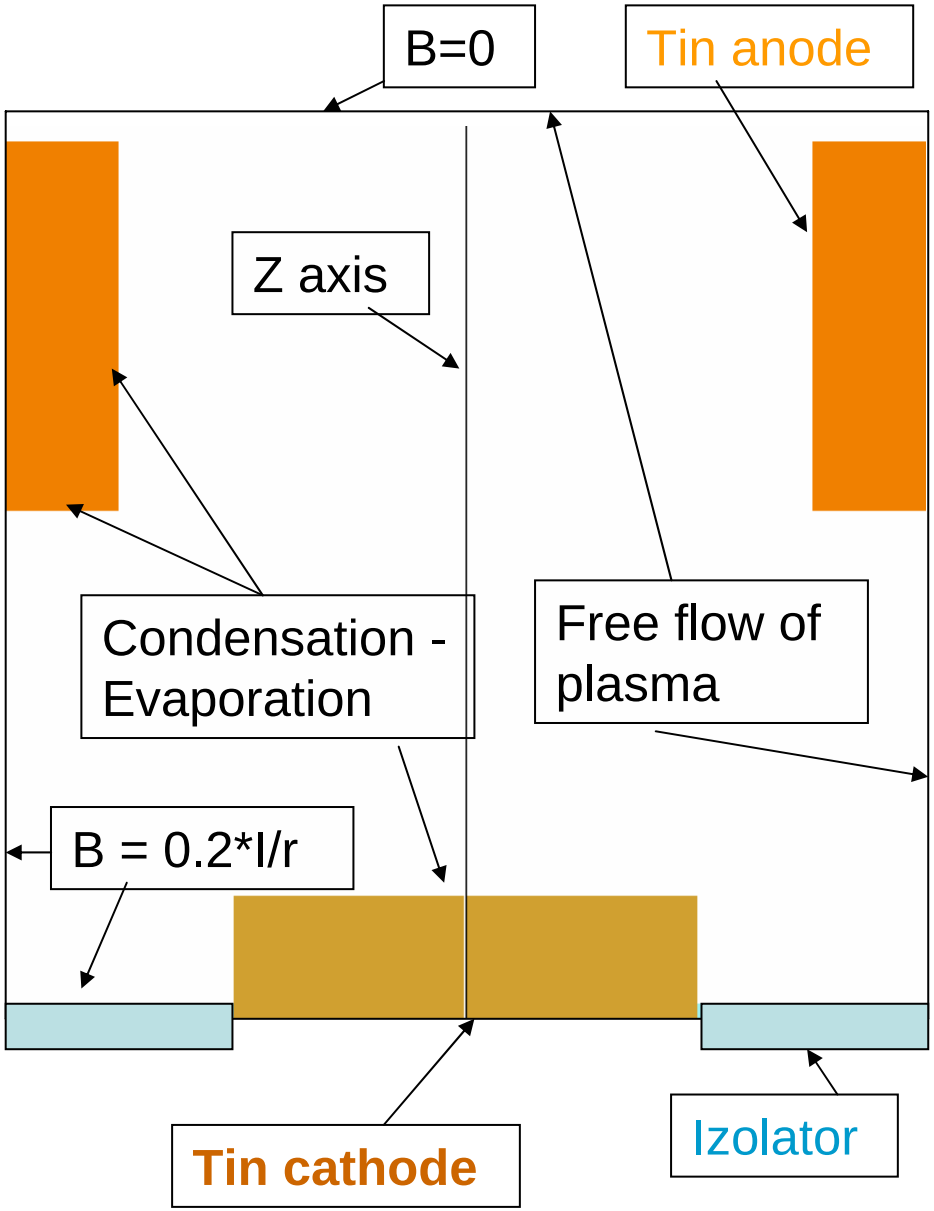
L = 11 nG

Initiating laser

Q_{laser} = 10 – 100 mJ

τ_{laser} = 23 ns

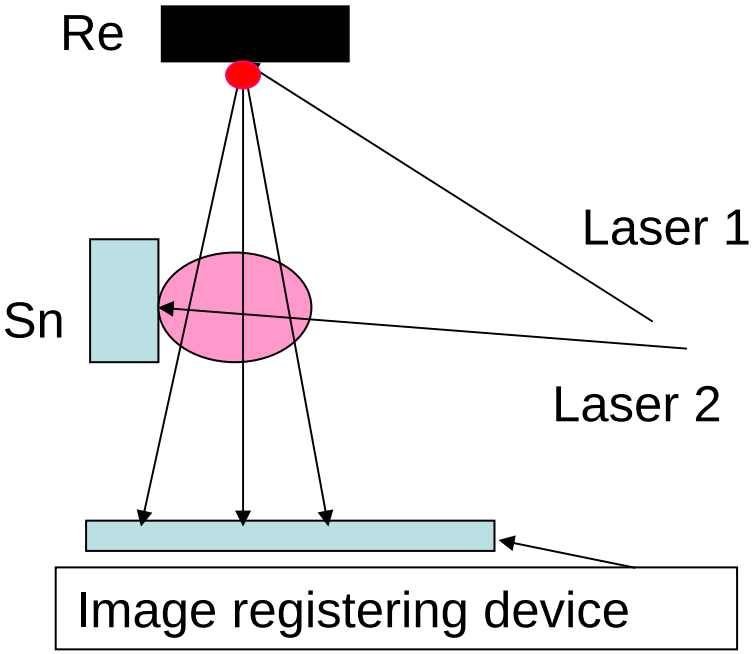
Simplified model of EUV source geometry and boundary condition

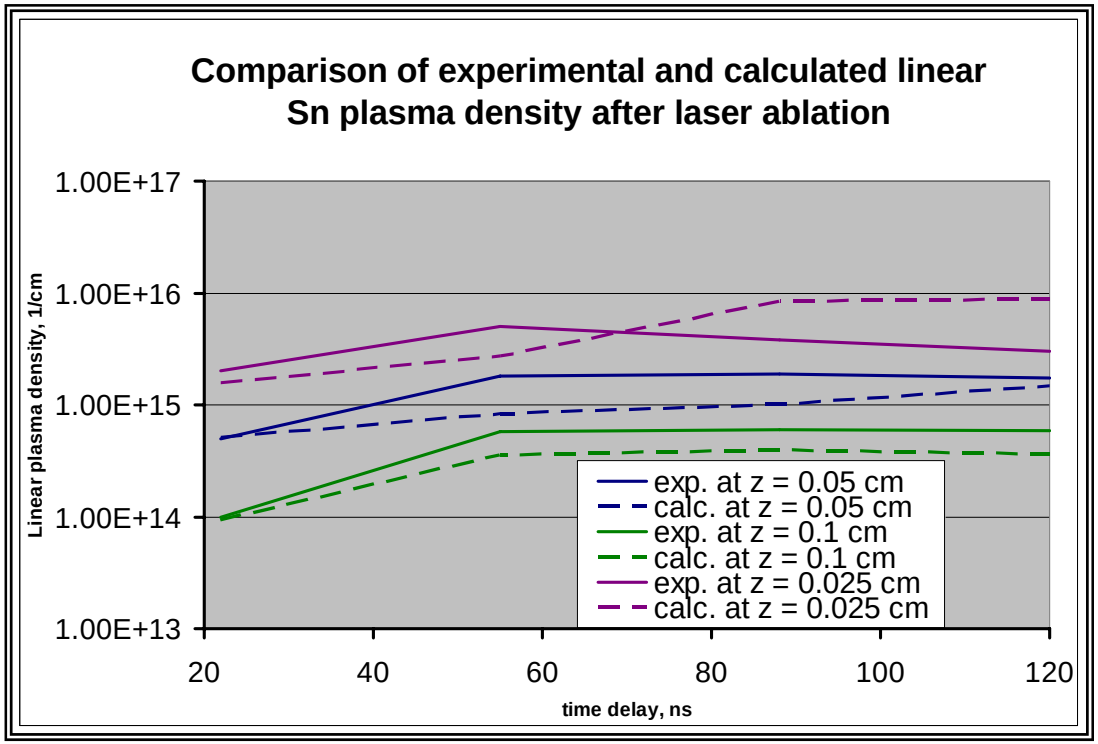


Different boundary conditions:

1. **For radiation: no reflection on all boundaries**
2. **For temperature:**
   - **Quasi-one dimensional calculation of cathode (anode) temperature distribution in depth; minimal mesh size – 1.e-5 cm**
   - **Constant temperature assumed on isolator surfaces**
   - **Zero temperature gradient on "Free flow" boundaries**
3. **Initiating laser light was supposed to be axis-symmetric and parallel to z axis with Gauss radial and temporal profiles**
4. **Laser light absorption in plasma of main laser pulse as well as one reflected from cathode surface were considered**

Phase 1: Laser ablation of liquid tin by Nd - YAG laser with pulse energy 30 mJ and HWHM ~ 23 ns; modeling and experiment



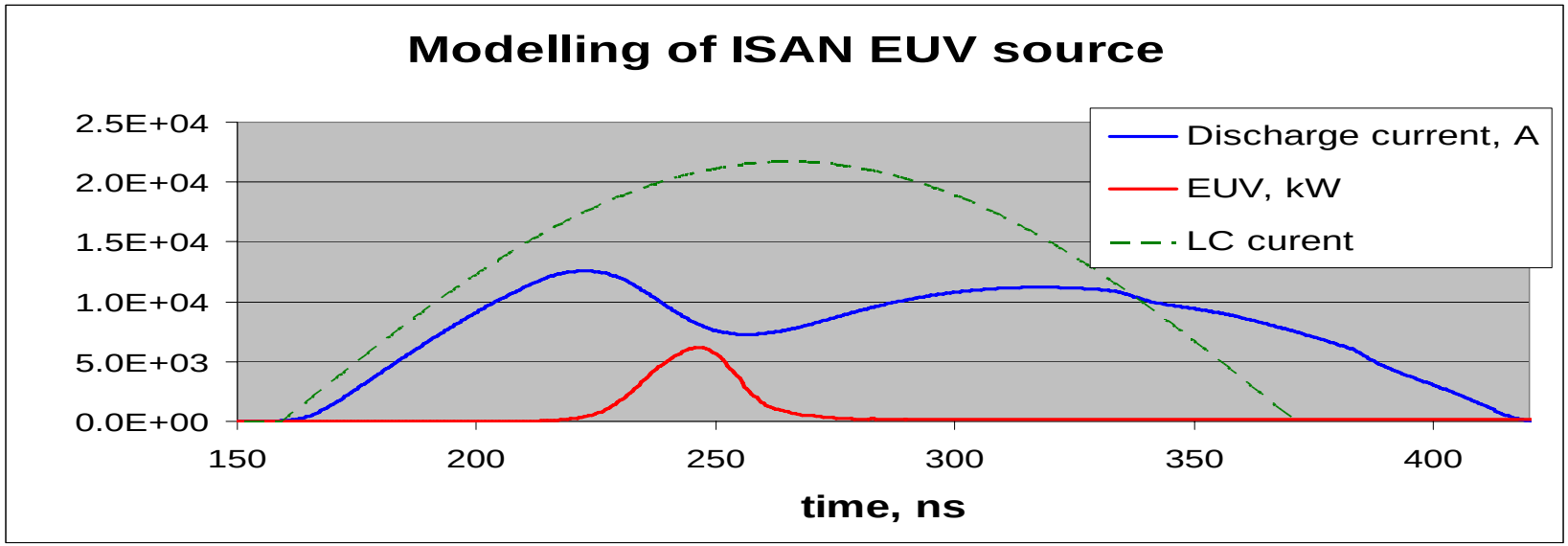


1. Plasma density was measured by VUV shadow technique
2. Calculation on homogeneous 120 x 120 grid for physical size 3 mm * 3 mm were done
3. Reasonable (factor two) agreement with experiment was shown

Parameters for modeling ISAN EUV discharged based source

- Capacitor Voltage – 3.6 kV
- Initial discharge inductance - 11 nH
- Capacity - 0.413 μF
- Laser energy – 30 mJ
- Laser HWHM – 23 ns
- Laser spot diameter – 200 μm
- Anode hole - 6 mm
- Cathode diameter – 4 mm
- Anode cathode gap – 3.5 mm
- Electro-transfer coefficient – 0.01 ion on one electron emitted by cathode surface

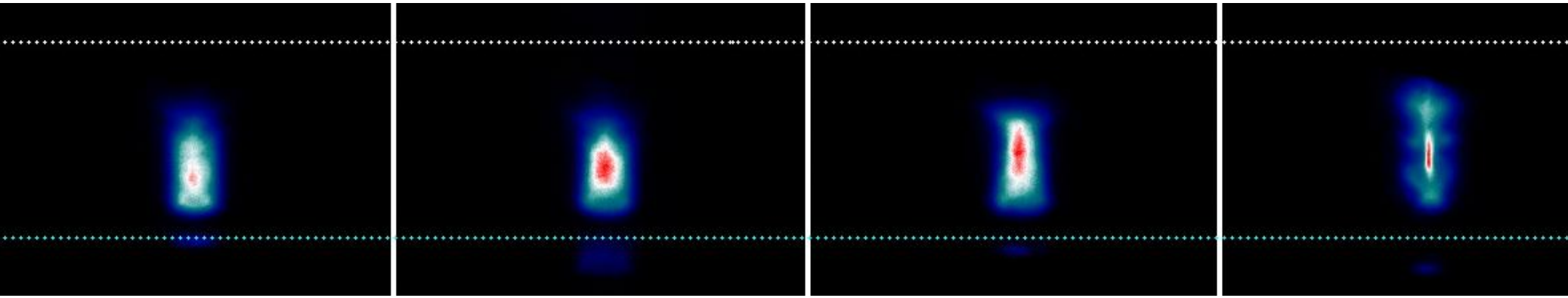
Time dependence of current and EUV radiation power



Look alike in model and in experiments:

- The same values of CE ~ 3% in experiment and in the model
- Pronounced peculiarity at maximum of current
- Maximal current about 11 kA
- first half-period is much larger then second one, which is close to LC defined
- EUV radiation coincides with current peculiarity

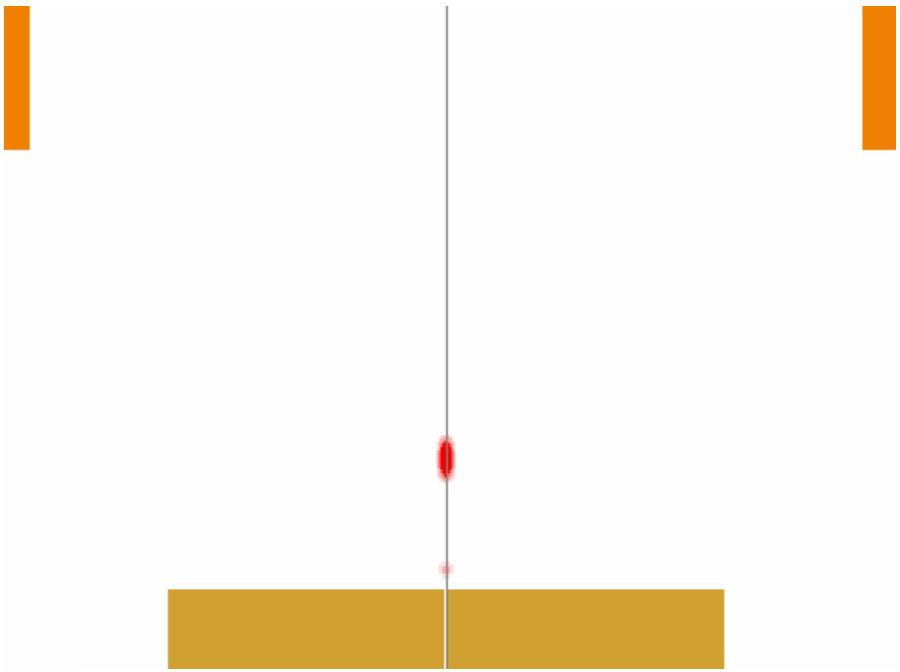
Time dependent EUV radiation, experiment



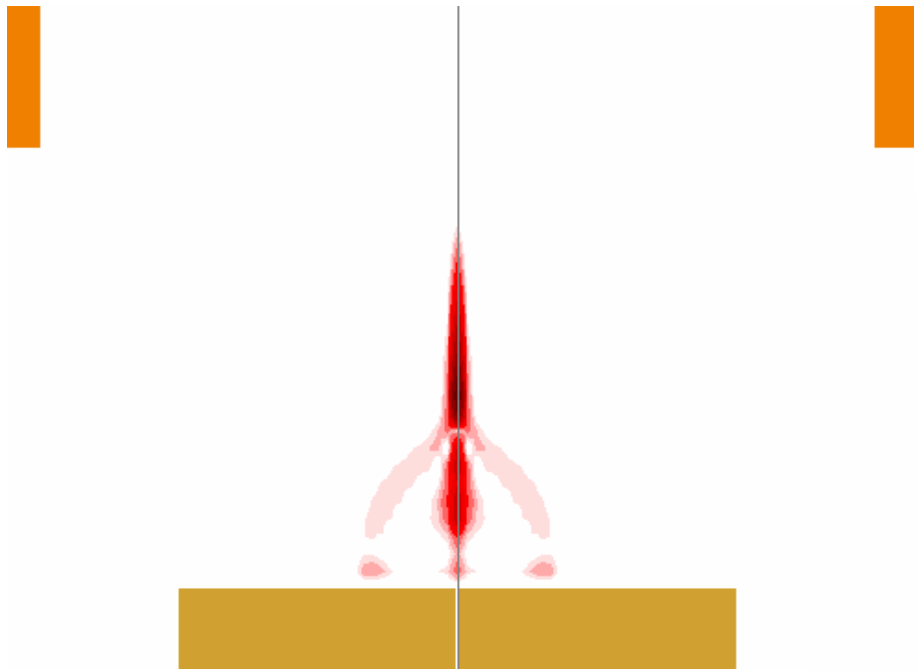
1. It is images in EUV region of spectra (λ<~ 25 nm)
2. Distance between marked on the pictures cathode (down line) and anode (up line) is 3.5 mm
3. EUV starts near cathode and move to anode
4. There is an image below cathode which is the result of EUV source reflection in cathode

Time dependent EUV radiation, modeled

EUV image t = 216 ns

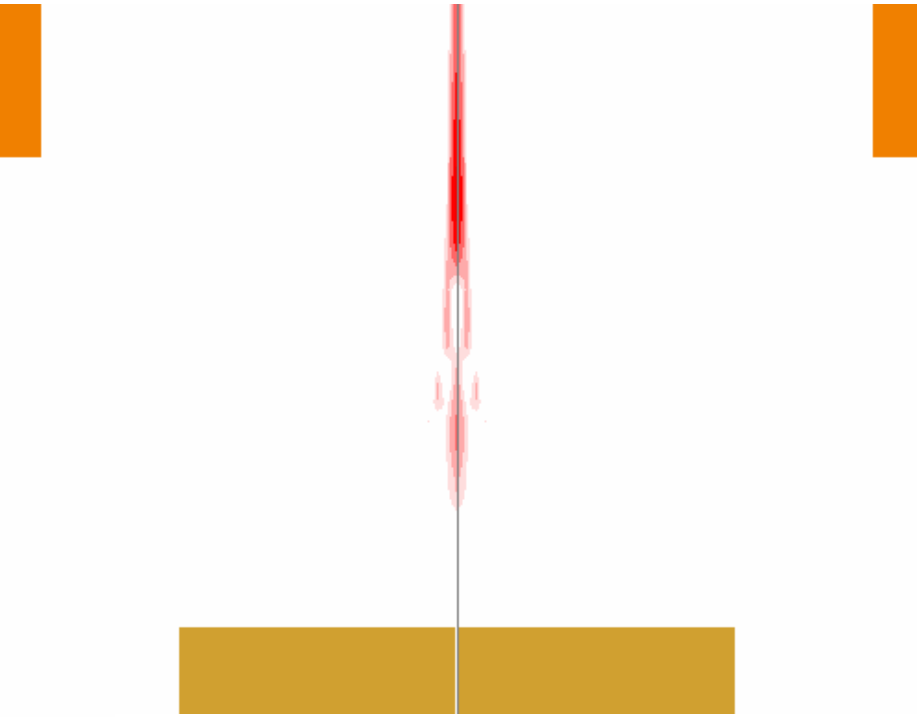


EUV image t = 250 ns

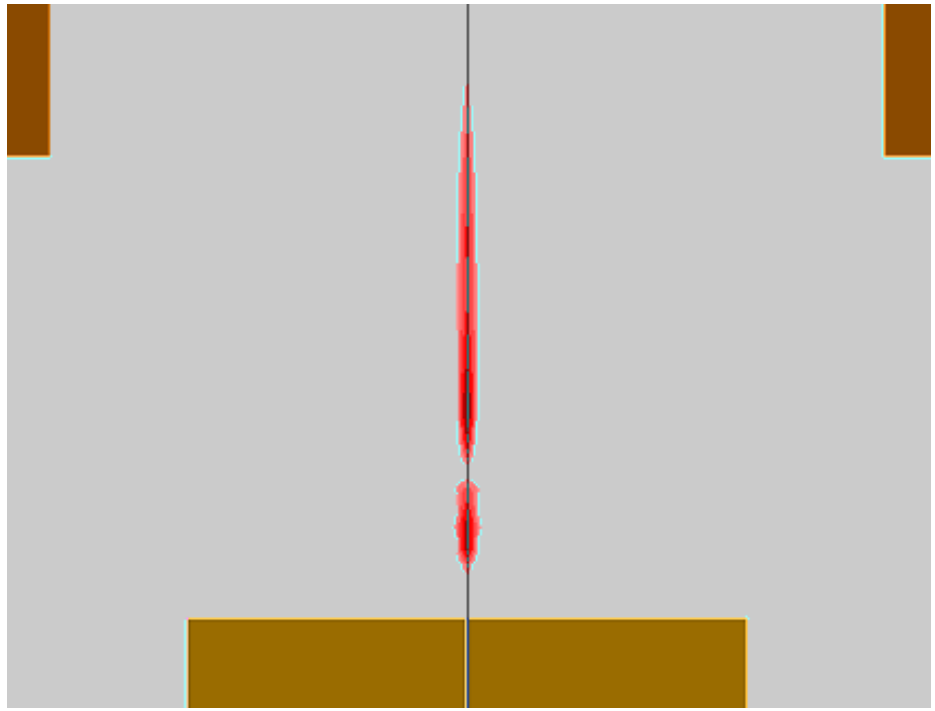


1. EUV radiation starts near cathode as in the experiment
2. EUV source is moving to anode as in the experiment

EUV image at t = 260 ns

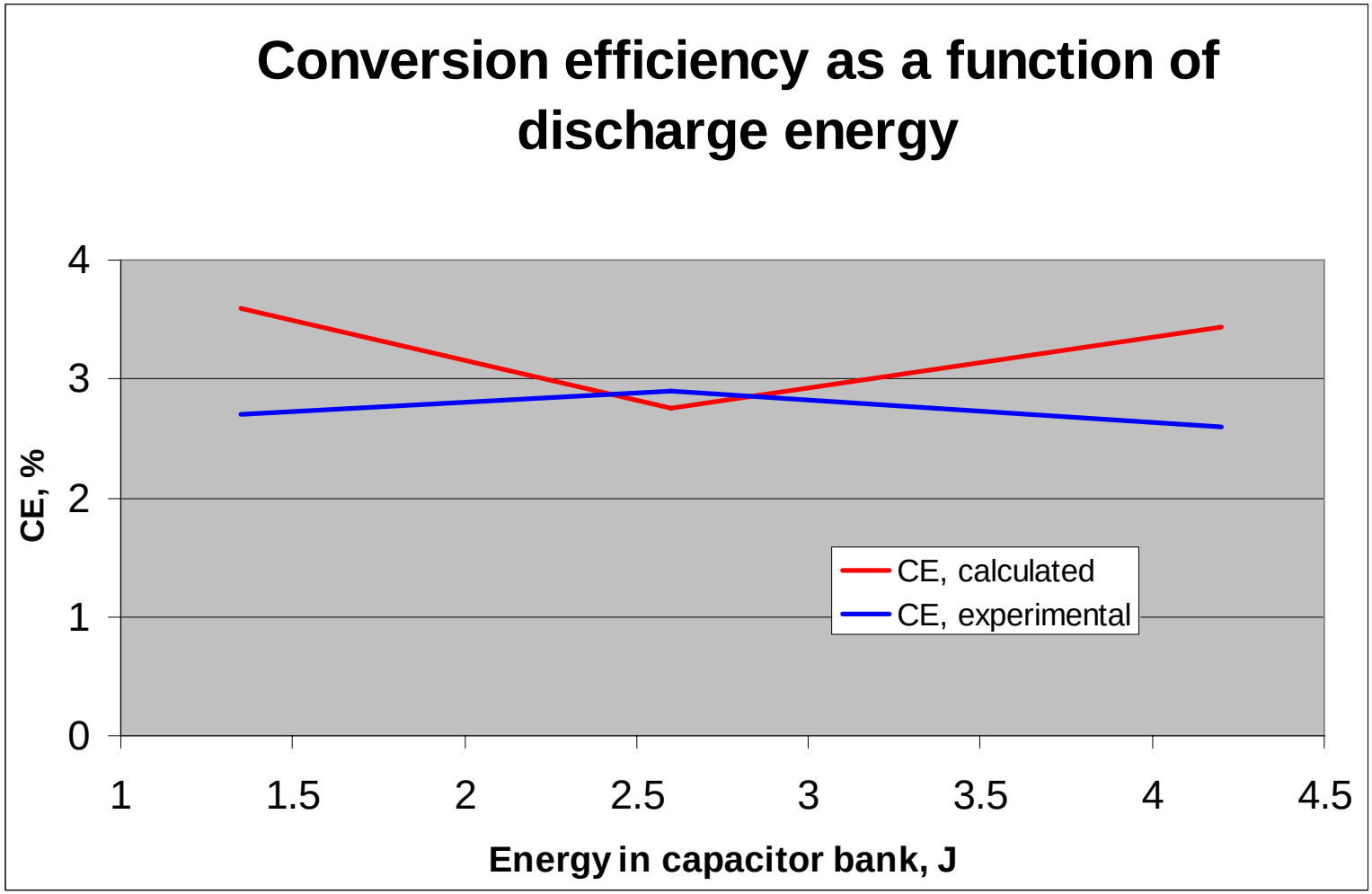


EUV image integrated over time



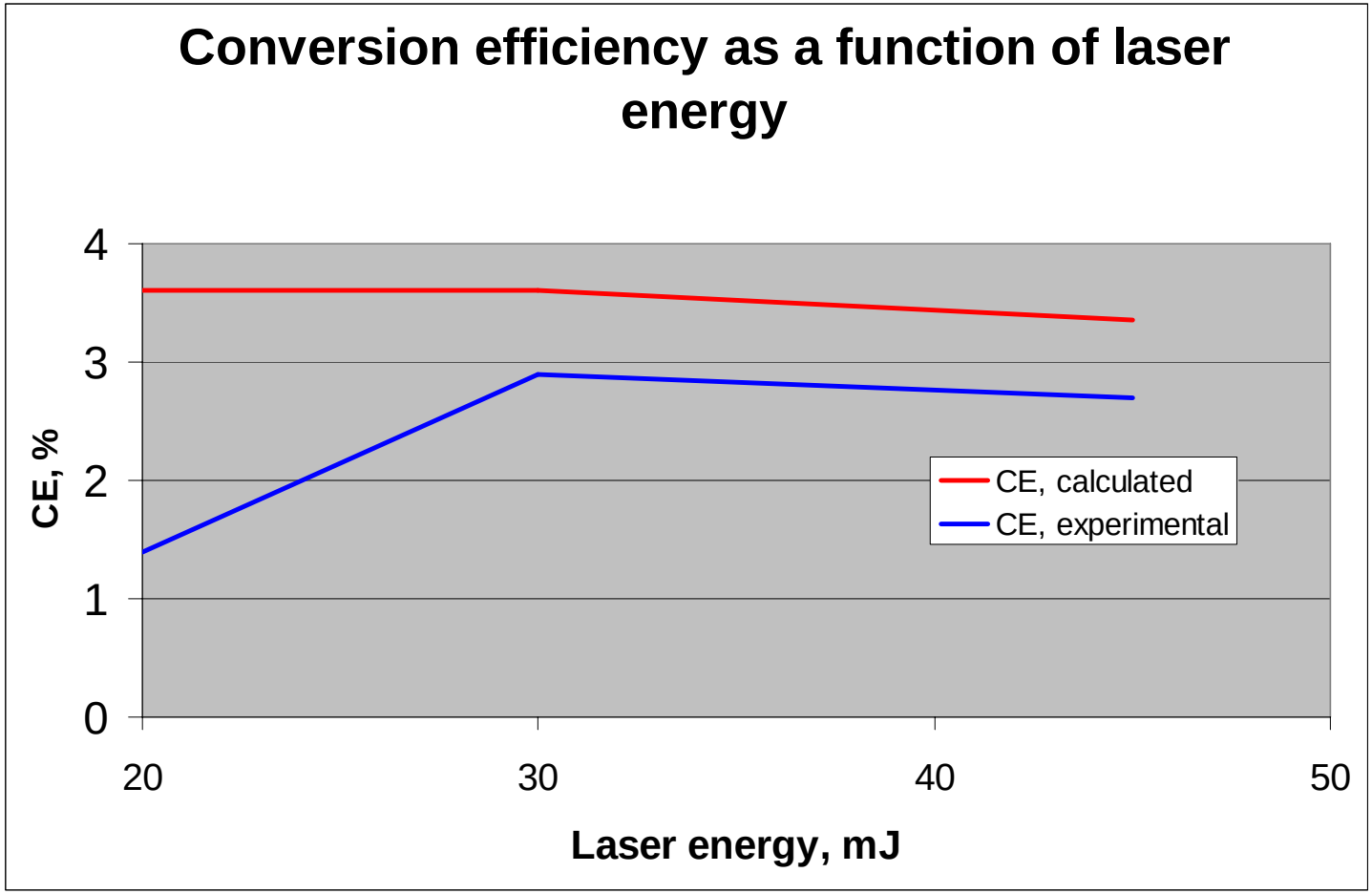
1. Effective length of EUV source is about 2 mm, as in experiment
2. Effective diameter is close to experimental one (~ 250 μm)
3. EUV source is moving to anode as in experiment

CE as a function of discharge energy



1. Close values of CE in the model and in the experiment

CE as a function of laser energy



1. Calculated and experimental CE are close at large laser energy
2. Overestimated calculated CE at low laser energy

Processor time consumption

Laser ablation of liquid tin

- homogeneous grid 120*120
- transfer of radiation in diffusion approach in 21 photon energy groups
- Non-homogeneous grid for liquid tin temperature 10*120
- calculation of first 80 ns of physical process time (expansion up to ~ 2 mm) needs about 1 hours on PC with one Intel 3 GHz processor

MHD calculation of plasma pinching

- initial density, temperature and so on parameters from "**Laser ablation"** step at 80 ns
- homogeneous grid 60*60
- transfer of radiation in diffusion approach in 21 photon energy groups
- mesh for liquid tin anode and cathode temperatures 3*10*60
- time of calculation of first half-period is about 1 hour on PC with Intel 3 GHz processor

Conclusions

1. **New two-dimensional (r, z) Euler MHD code RZLINE for modeling EUV sources was created.**
2. Newly developed **THERMOS-BEELINE** code was used for modeling of radiative phenomena
3. At modeling of ISAN EUV source several experimental results have been well described:
   - Absolute value of conversion efficiency
   - discharge current and EUV signal time history
   - Axial and radial size of EUV source
   - Observation of zippering effect of moving of EUV image from cathode to anode
4. **And the code is very fast (~ 1 hour on one run on PC)**