On the Optimal Choice of the Wavelength of Laser Radiation for LPP EUV Sources

V. V. Ivanov[1,2], V.M. Krivtsun[1,2], V.V. Medvedev[1,2], and K.N. Koshelev[1,2]

[1] *Institute of Spectroscopy of the Russian Academy of Science (ISAN), Moscow, Troitsk, Russia*
[2] *EUV Labs, Moscow, Troitsk, Russia*

All modeling in this presentation were done using RZLINE code

1. RZLINE is a 2D (**two-temperature, single-fluid**) and 3D (**one-temperature, single-fluid**) Eulerian radiative hydrodynamics code with a non-homogeneous non-adaptive moving grid.

2. RZLINE solves the hydrodynamics equations with laser absorption and thermal conduction coupled to the equations of spectral radiative transfer in axially symmetric (r, z) geometry (2D) and (x,y,z) geometry (3D). The last was solved in multi-groups approximation by 3D ray-tracing procedure.

3. Multi-groups approximation with more then 20 000 groups can include Doppler effect.

4. Any grid-cell can be a mixture of liquid phase and gaseous(plasma) state.

5. Ion distribution in plasma can be taken from table data (stationary distribution at given density, temperature and radiation field intensity).

RZLINE Input/Output

laser parameters

- laser energy
- laser wavelength
- spatial profile: hot/cold spot, beam size
- temporal profile: pedestal, rise time, peak power
- Up to three independent laser beam with different parameters including wavelength and caustic can be used

target

- Many types of axis-symmetric target are possible and can be placed in any position in caustic , e.g.:
  - droplet
  - liquid multi-shell target
  - liquid- gaseous volume-like target given as a file from external source

RZLINE

Fast PC based RZLINE code with simple input data allows to do wide range optimization on different parameters without using supercomputer with its complex infrastructure

- Full radiation spectrum : of time, wavelength, radial and axial position, polar and azimuth angles
- CE for In-Band EUV of time and polar angle
- Realistic EUV images in different wavelength regions and at different polar angles
- Energy balance
- Ion energy distribution of polar angle, charge and time
- Laser absorption as f(r,z) and Laser reflection as f(polar_ angle)
- Spatial/temporal plasma parameter maps

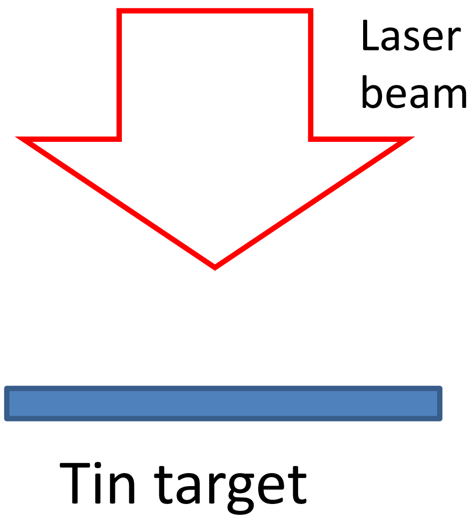
- Density of liquid state and different ions
- Ion and electron temperature
- Velocities maps as for liquid as for plasma
- Pressure

Content

- **On the Optimal Choice of the Wavelength of Laser Radiation for LPP EUV Sources**
  - **HVM source**
  - **Actinic source**
- **Radiation hydrodynamic simulations of $\lambda = 2$ μm irradiation of tin micro-droplets**
  - **Electron density and temperature profiles**
  - **CE and EUV spectra**
  - **Doppler effect in simulation of spectra in LPP EUV sources (larger CE were calculated)**
- **3D version of RZLINE in HVM case**
  - **Electron density and temperature profiles**
  - **EUV images**

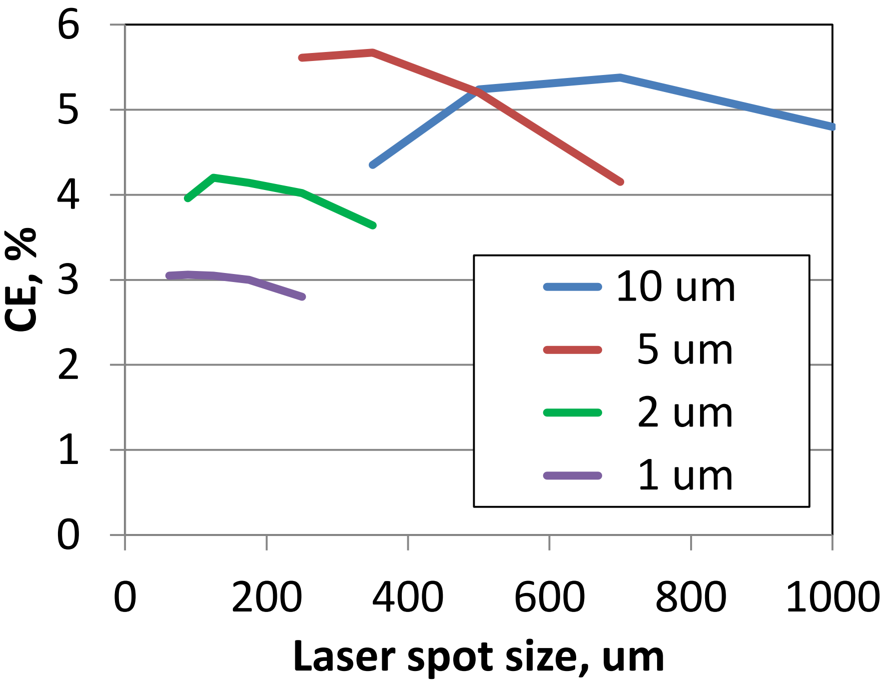
On the Optimal Choice of the Wavelength of Laser Radiation for LPP EUV Sources

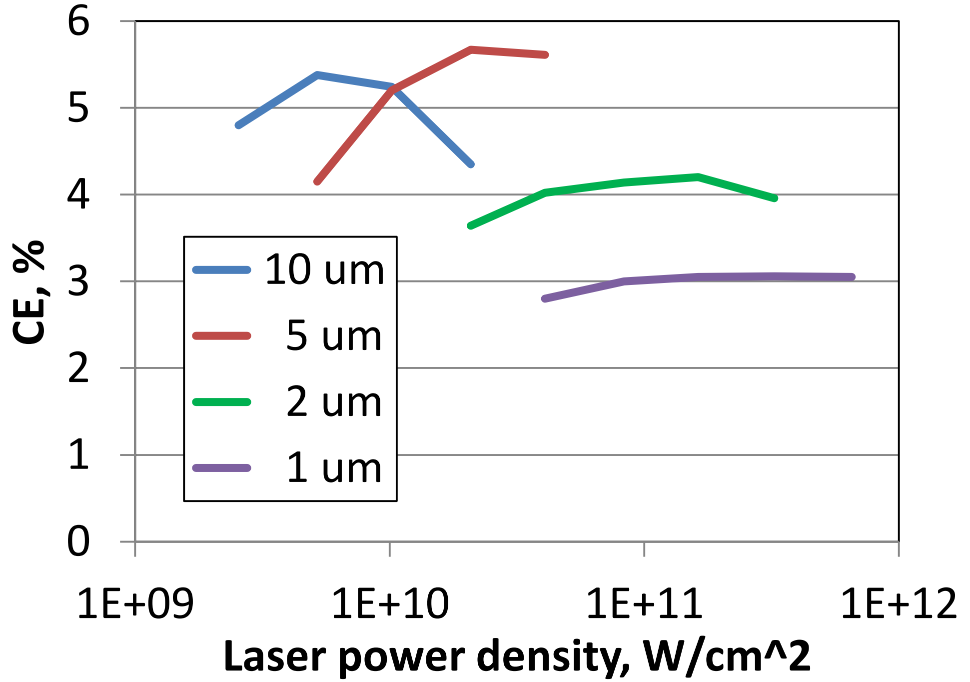
The idea is to show, that different wavelength may be optimal for different task. HVM-like and actinic-like sources were chosen as an examples.



1. Disk size is made of 30 um droplet (by pre-pulse).
2. Disk has the same size as laser beam size
3. Laser beam size: 60 – 1000 um (1/e^2)
4. Gauss laser space and time distribution
5. Laser duration 10 ns (FWHM)
6. Round polarization of laser beam was used which is the only choice in 2D modeling
7. Wavelength: 1,2,5 and 10 um
8. Laser pulse energy 0.2 J   (HVM-like case)
9. Laser pulse energy 0.01 J   (actinic –like case)
10. Radiation transfer table used: from KIAM, v11n_corr2 (95 wavelength groups , thus Doppler effect is not taken into account here)

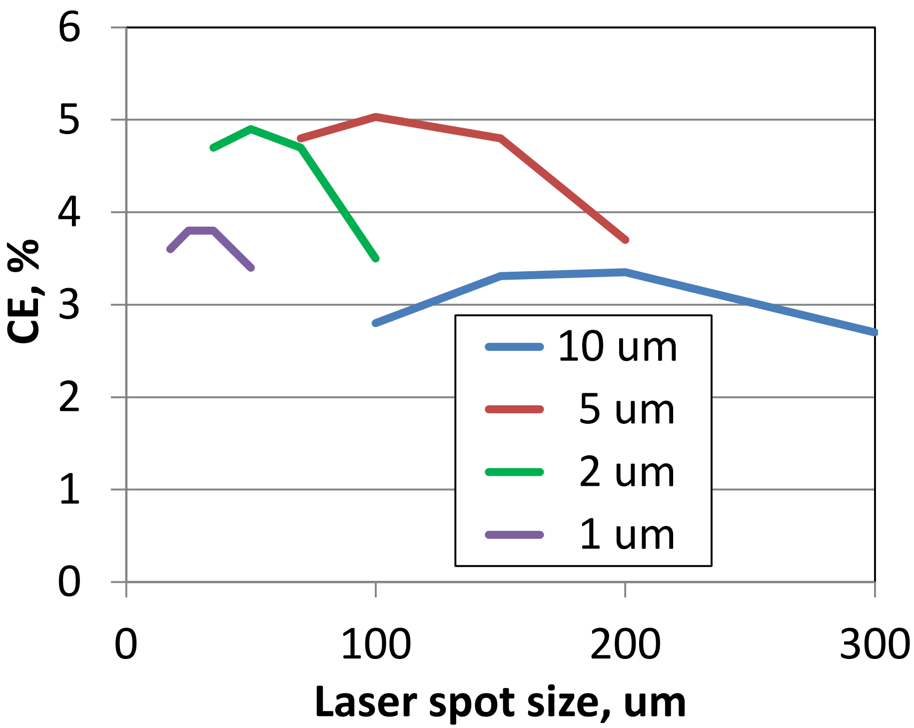
CE as a function of wavelength and laser spot size (HVM-like case)

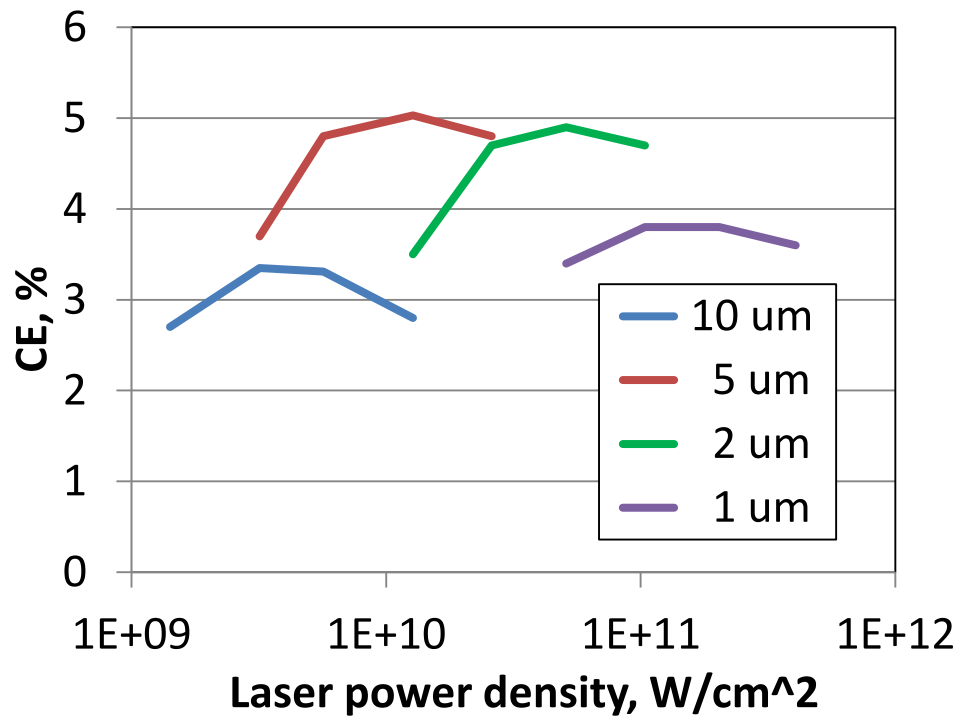




1. Maximal CE in HVM-like source is a function of needed laser spot size (~EUV source size) is reached at wavelength:
   - 2 um for 30 – 200 um
   - 5 um for 200 – 500 um
   - 10 um for > 500 um
2. Absolute maximum of CE ~5.7% is reached at 5 um

CE as a function of wavelength and laser spot size (actinic-like source)





1. 20 times decrease of laser energy shift optimal wavelengths essentially:
   - CE at 10 um wavelength decreased in 2 times, still it remains optimal at laser spot more then ~250 um
   - CE at 5 um is decreased still it is rather large ~5%
   - CE at 2 um is increased essentially (to 5%) and is forming absolute maximum together with 5 um wavelength
2. Looks like 1 um or even smaller wavelength can be optimal at even smaller laser spot or smaller laser energy or shorter laser durations

Radiation hydrodynamic simulations of $\lambda = 2\ \mu m$ irradiation of tin micro-droplets

All variants from proposal:

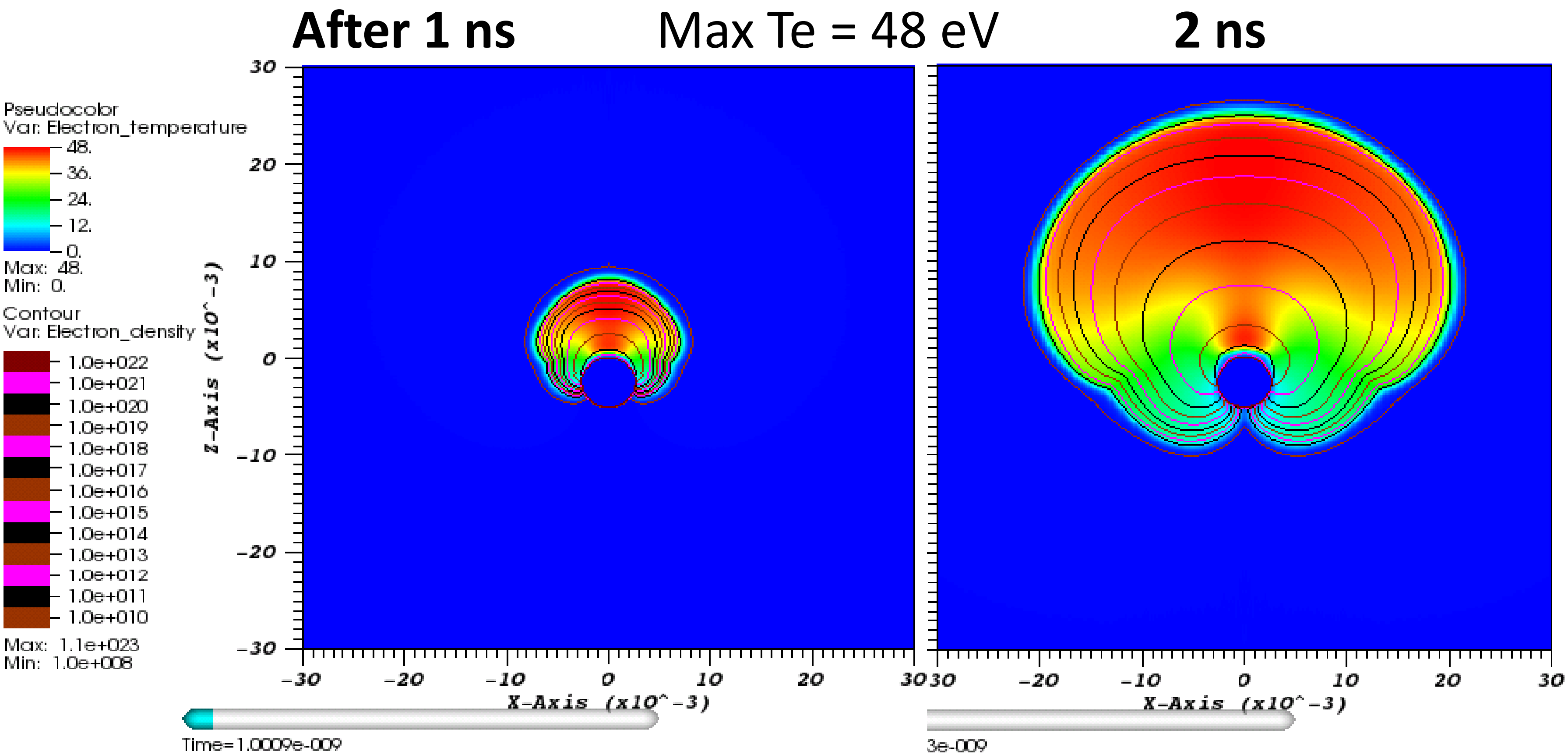
1. Droplet 25 and 50 um
2. Laser intensity 5.e8, 1.e9, 5.e9, 1.e10, 5.e10 W/cm^2
3. Laser duration 10 ns (Box-shape).
4. Laser spot size 100 um
5. Round polarization

Parameters of basic variant (more data will be given):

1. Droplet 50 um
2. Laser intensity 1.e10 W/cm^2
3. Laser duration 10 ns (Box-shape) .
4. Laser spot size 100 um

CE and spectra will be given for one direction only (opposite to laser beam direction)

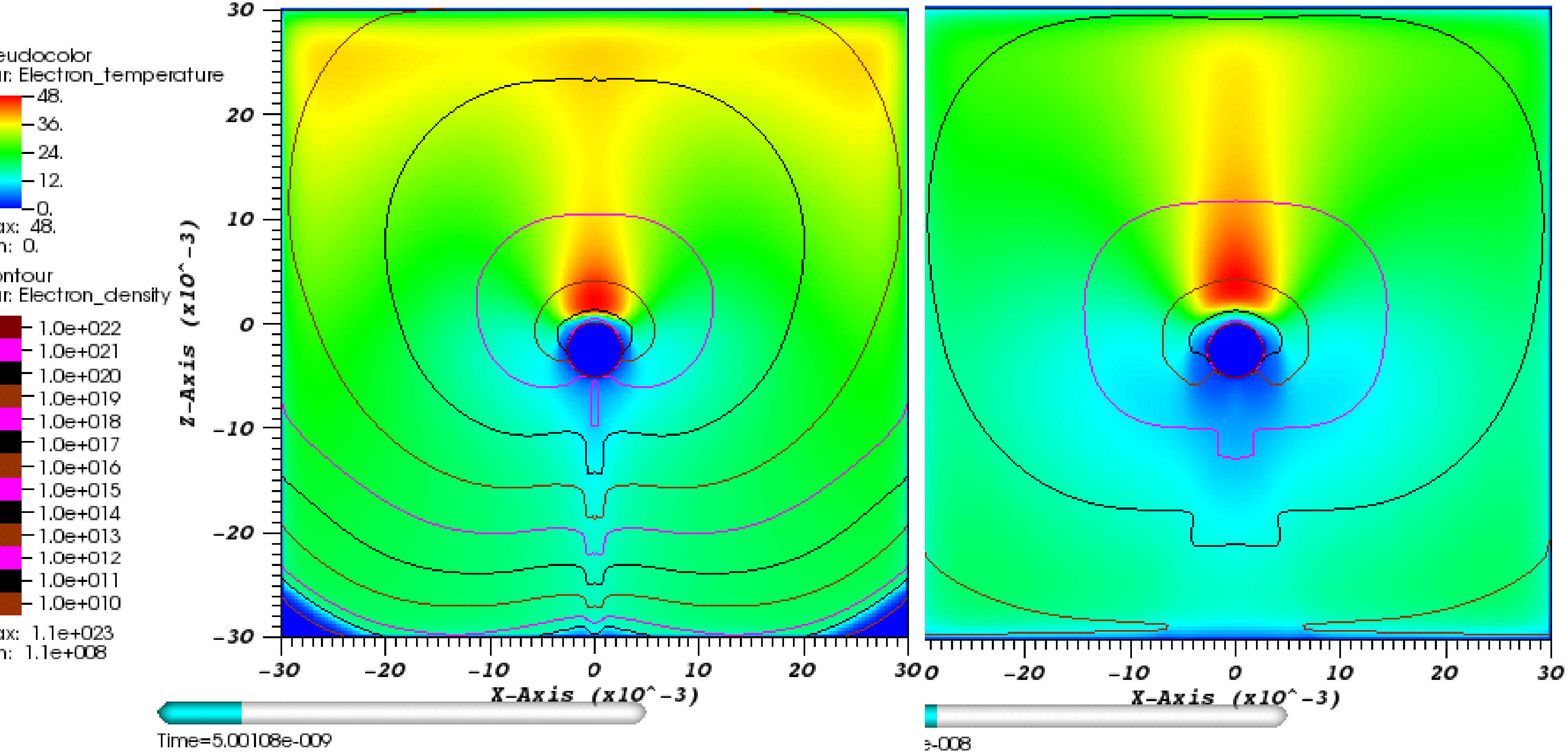
Electron density and temperature profiles



1. Parameters of basic variant (see slide 8) were used
2. Quasi-spherical plasma expansion occur , neighboring contour line of electron density are differs in ten times
3. Form of droplet is practically not changed

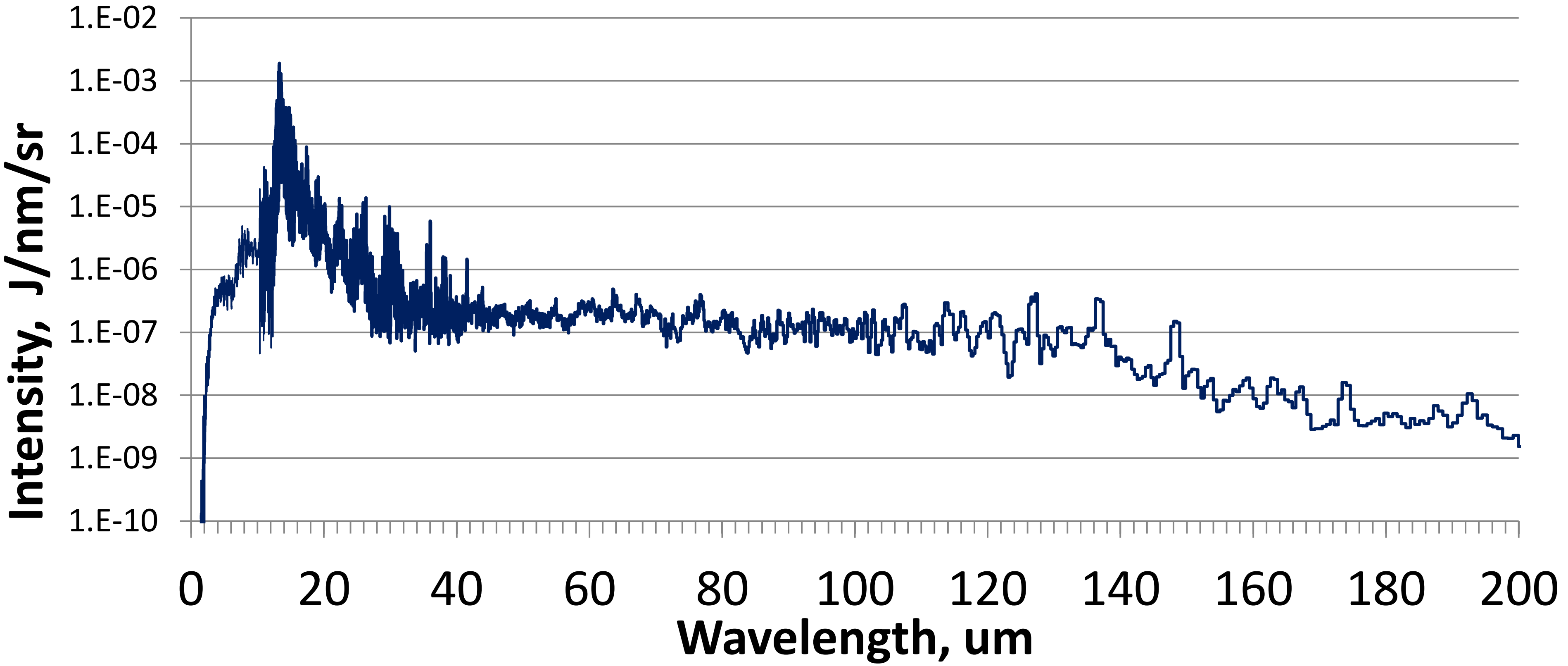
Electron density and temperature profiles

After 5 ns Max Te = 48 eV **10 ns**



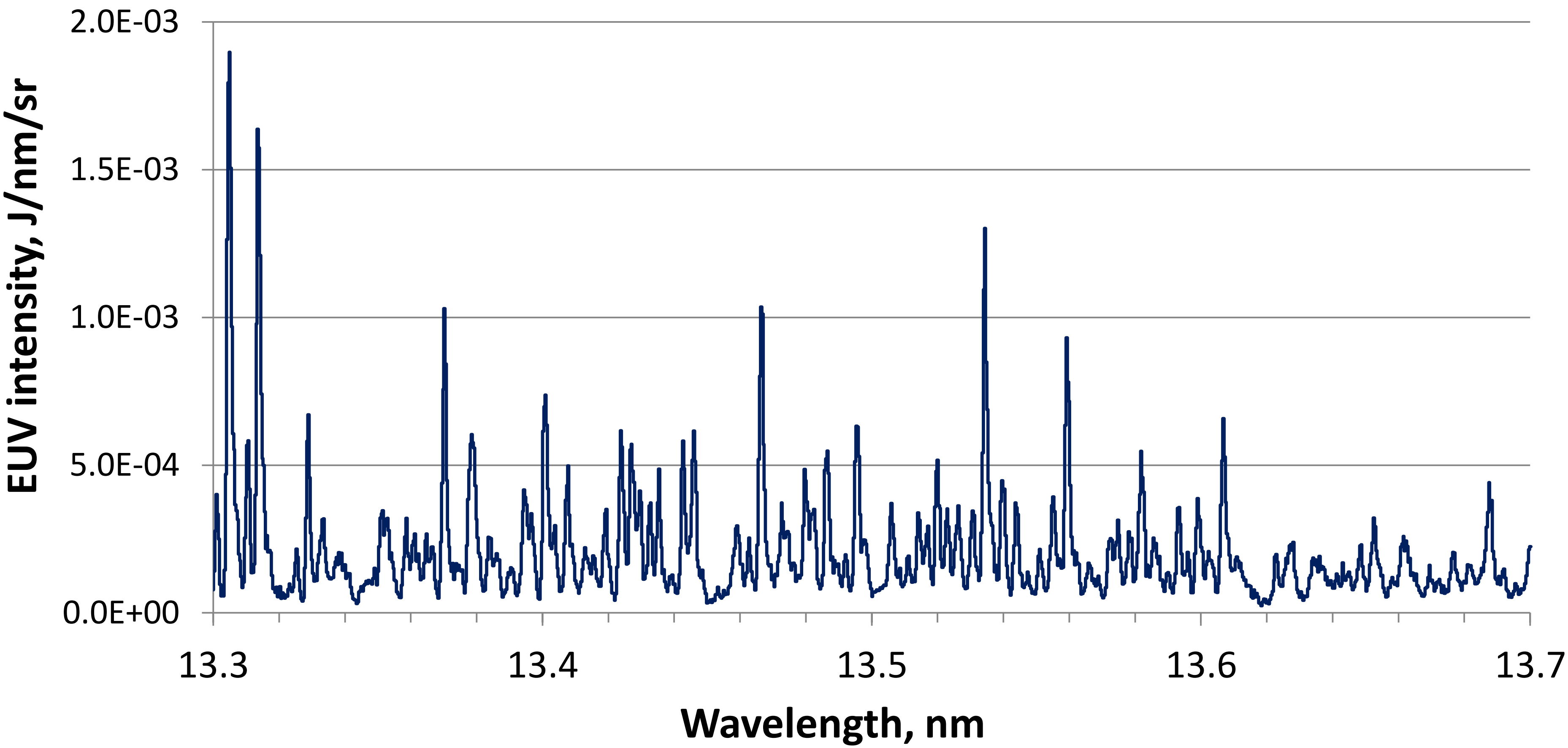
1. Plasma density profile near droplet is nearly established
2. Still plasma density is changing far from droplet and under droplet
3. Form of droplet is practically not changed

Calculated EUV-UV spectra



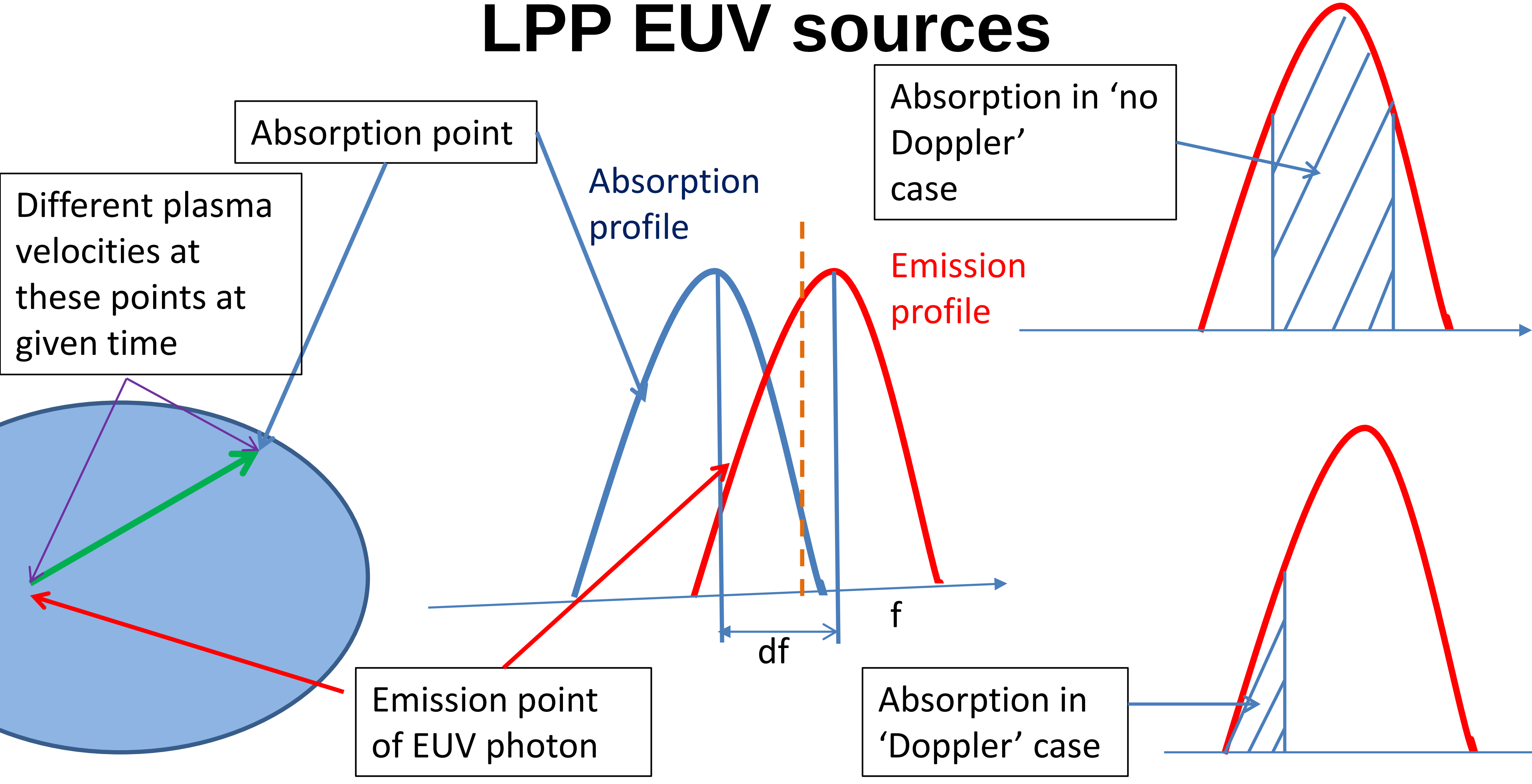
1. Radiation tables used were constructed in Keldysh Institute of Applied Mathematics (KIAM) using code THERMOS (**Published**: Nikiforov A.F., Novikov V.G., Uvarov V.B. Quantum-Statistical Models of Hot Dense Matter. Methods for Computation Opacity and Equation of State. Birkhauser, Basel, Switzerland, 2005. 428 pages. ISBN 987-3-7643-2183-8.
2. They include ~20 000 wavelength groups, main part is distributed in 12 – 15.5 nm region, where most part of energy is emitted

Calculated in-band EUV spectra



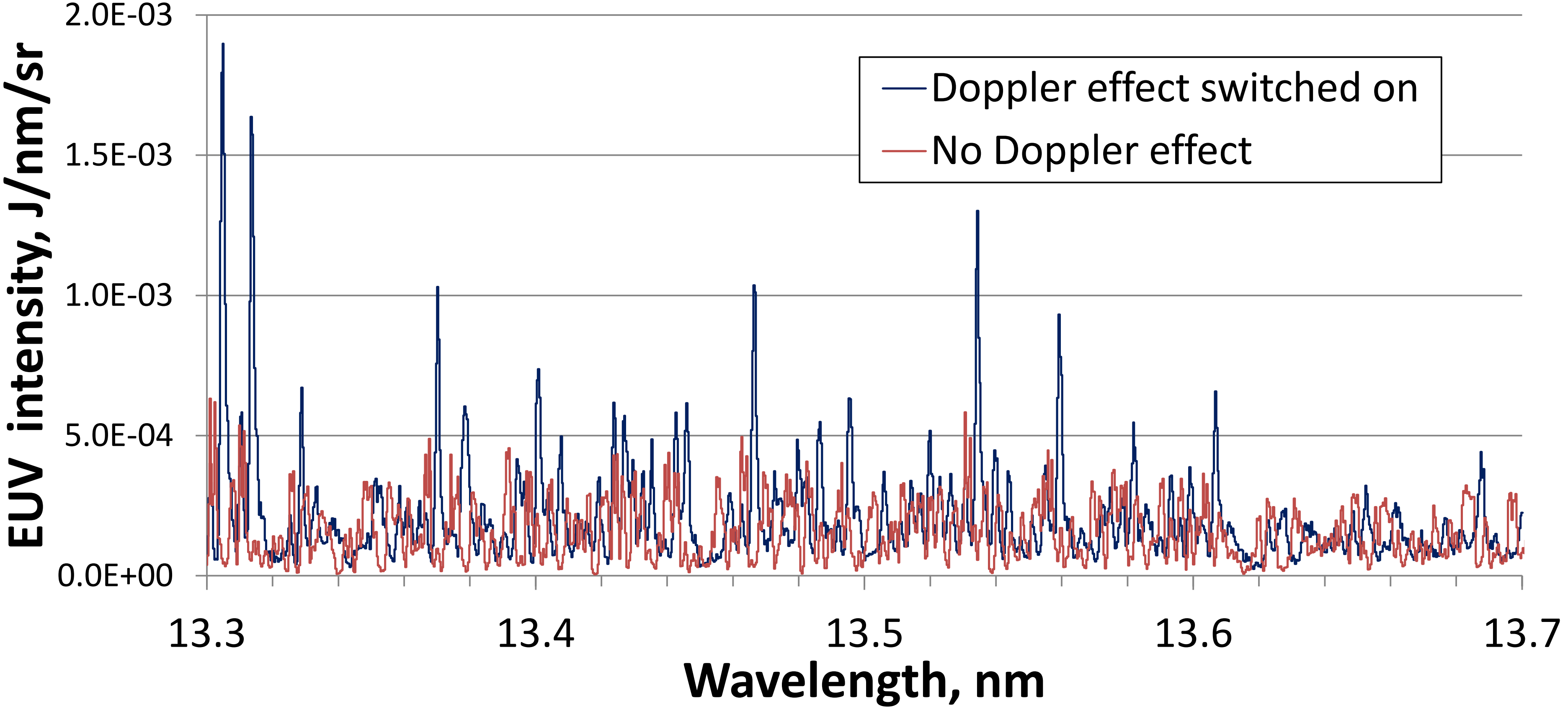
1. Wavelength resolution is 0.0004 nm
2. The question may appear: why we used that detailed grid in wavelength? The answer – this grid allow us to take into account Doppler effect, see next slide

Doppler effect in simulation of spectra in LPP EUV sources



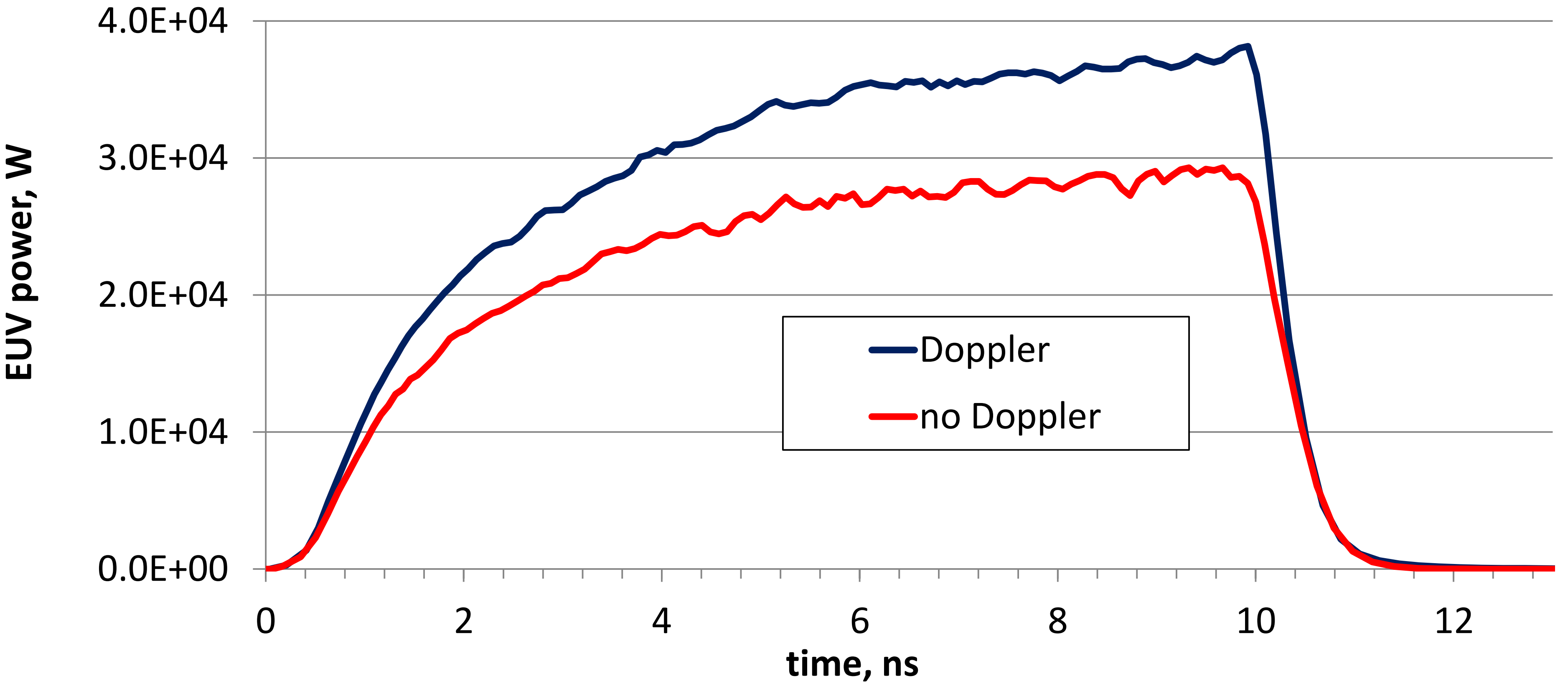
1. Frequency shift in emission and absorption profiles df=dV/c*f
2. At dV ~= Vs (sound velocity ~= 3.e6 cm/s) one will have df/f ~1.e-4
3. Used radiation table have df/f ~= 3.e-5 in energetically important region, so they suit well for the task.
4. dV is defined by 3 vectors: plasma velocities in emission and absorption points and vector

Calculated in-band EUV spectra with and without Doppler effect



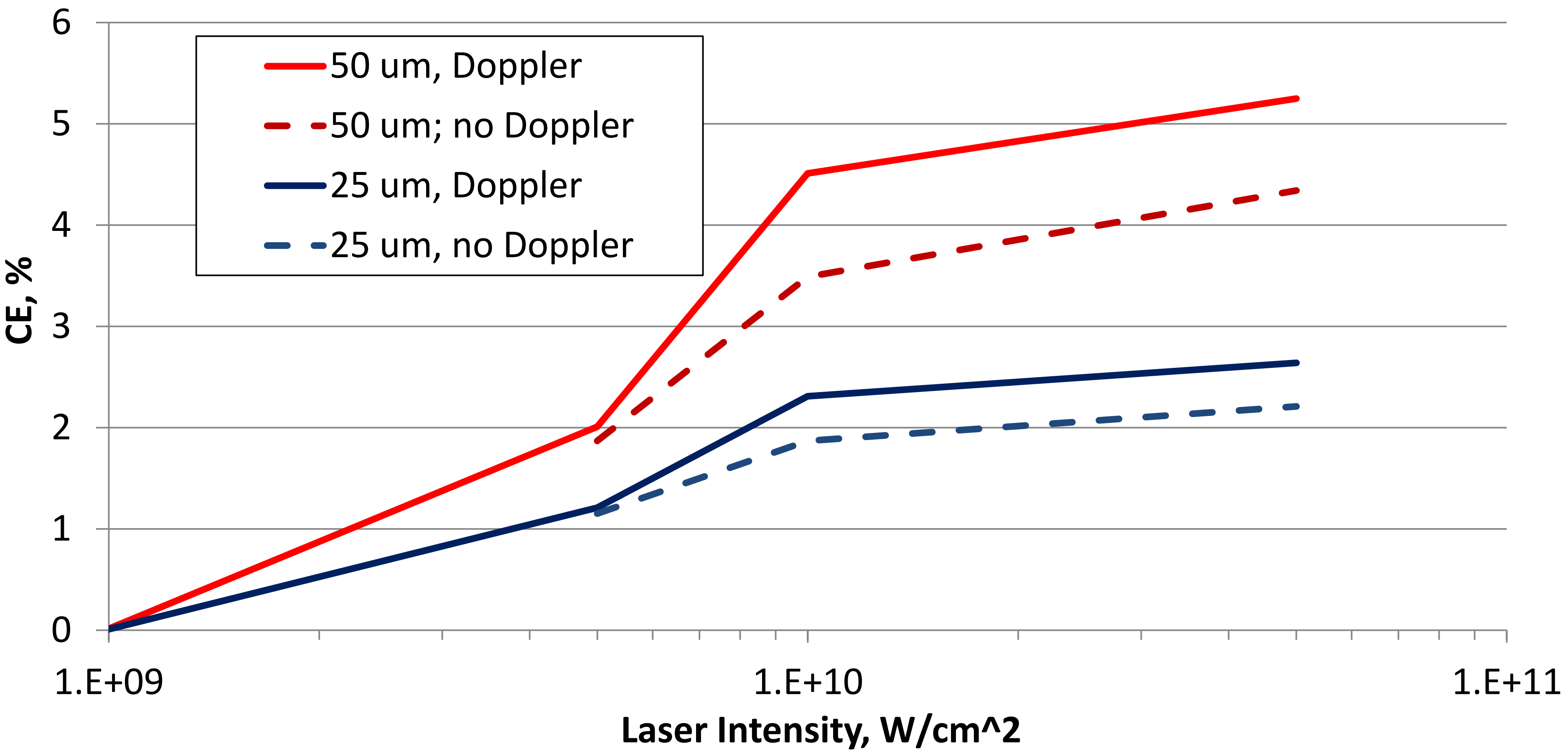
1. Parameters of basic variant, see slide 8
2. **EUV intensity in some wavelength groups may be up to 3 times higher if Doppler effect is switched on in modeling**
3. Still integral influence of this effect is not seen here

Calculated EUV in-band power as a function of time



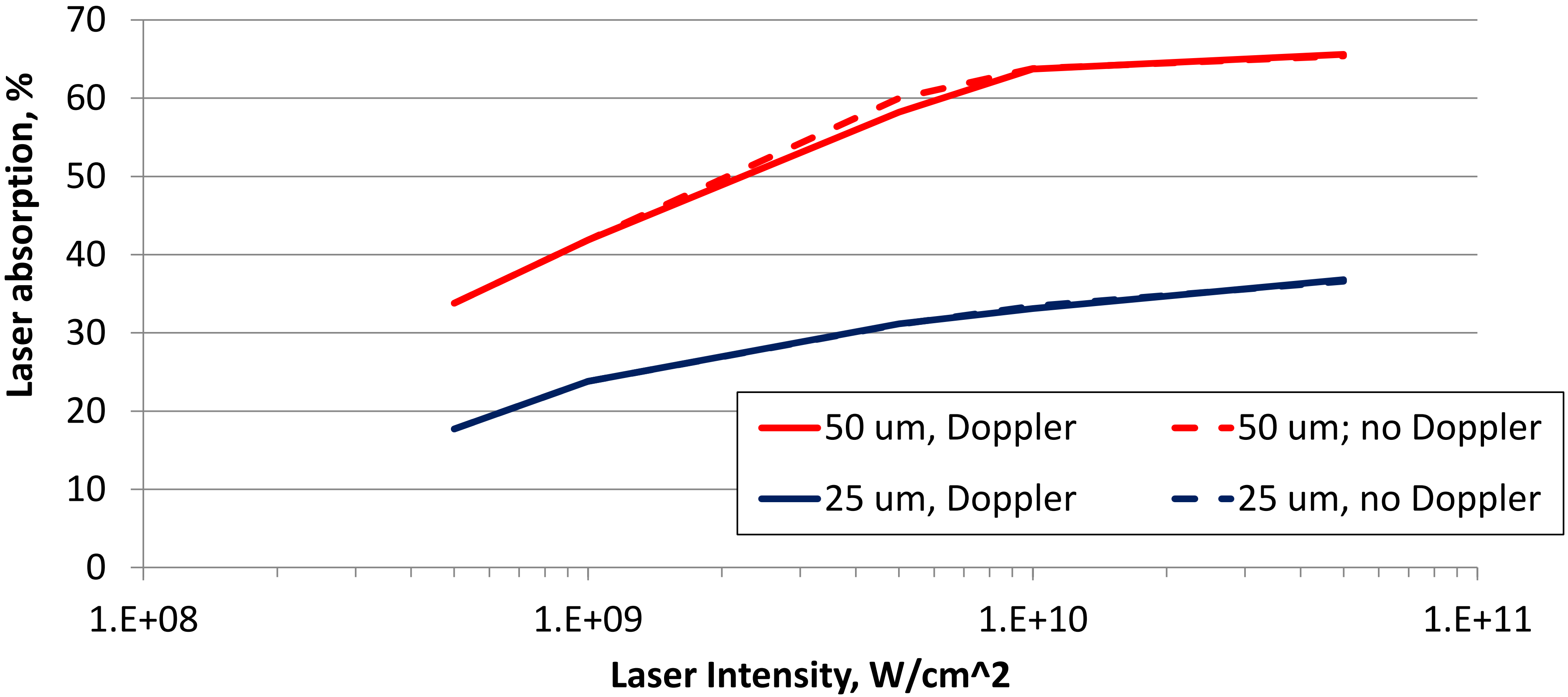
1. Parameters of basic variant, see slide 8
2. Doppler effect start to be important after 1 ns of plasma expansion
3. **If Doppler effect is taken into account it is changing essentially calculated EUV in-band power (and CE**) in this variant. For other variants see next slide.

Calculated CE as a function of laser intensity with and without Doppler effect



1. Laser wavelength 2 um, 10 ns; laser spot size 100 um
2. **Doppler effect is worth to take into account, especially at larger laser intensities**
3. Additional calculations (not shown here) shows that this effect is also important in cases of 5 and 10 um laser wavelengths

Calculated absorption of laser power as a function of laser intensity



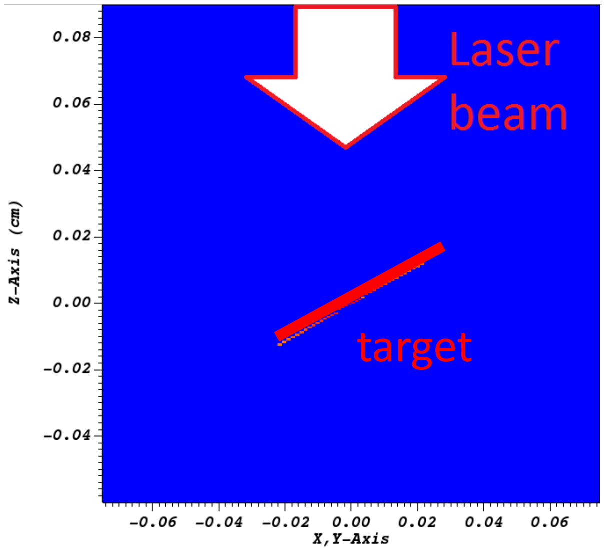
1. Plasma is expanding to larger radius at increasing of laser intensity, which lead to better coupling of laser beam and plasma.
2. Laser spot size in case 25 um droplet is not optimal, so absorption is so small
3. Doppler effect is practically not important in process of absorption of laser energy

3D version of RZLINE in HVM

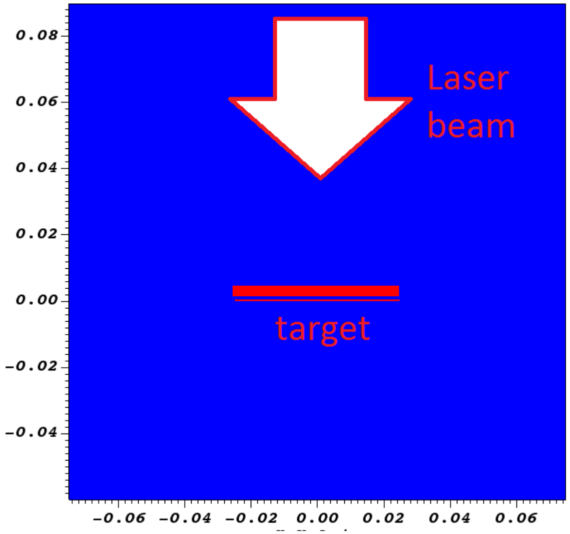
1. CO_2 laser - energy 0.15 J
2. Laser is Gauss in time and space
   - Duration 15 ns FWHM
   - Spot 500 um (1/e^2)
   - Round polarization was supposed
3. Target is a disk
   - Of 25 um droplet
   - Diameter 500 um, const thickness, disk centre is on laser axis
   - Angle between laser axis and normal to surface is 30 degree

It is possible to run the code as on server as on personal computer

Y = 0 cross-section

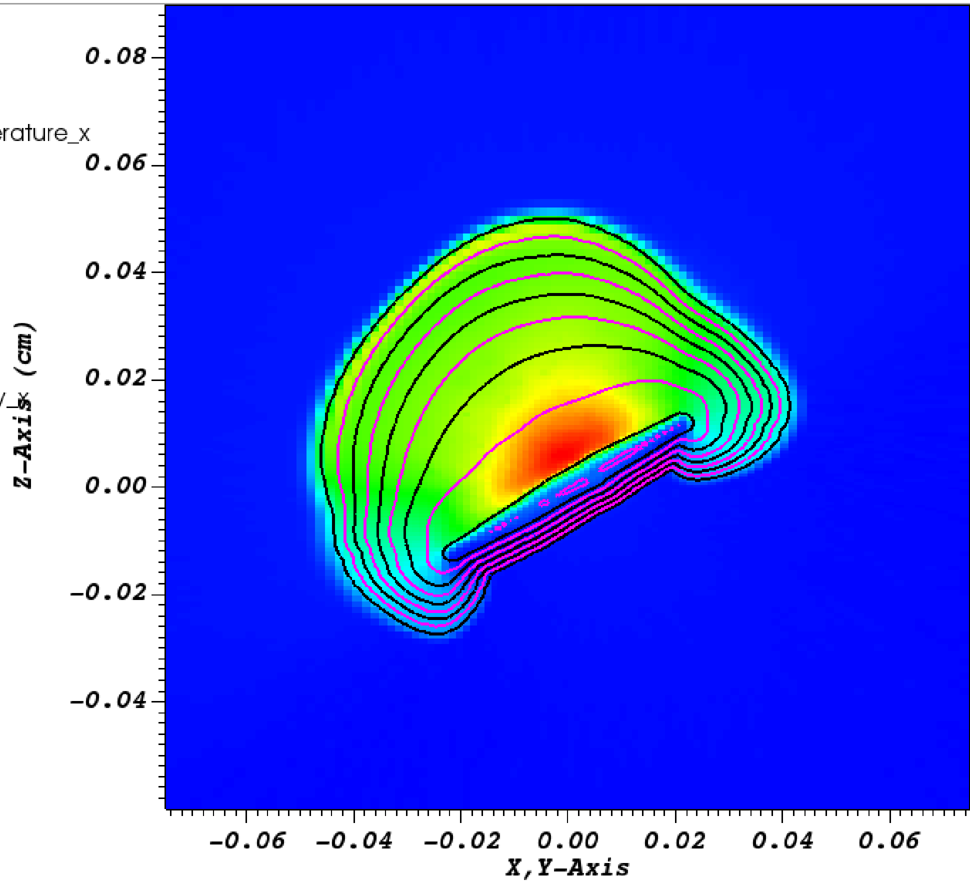


X = 0 cross-section

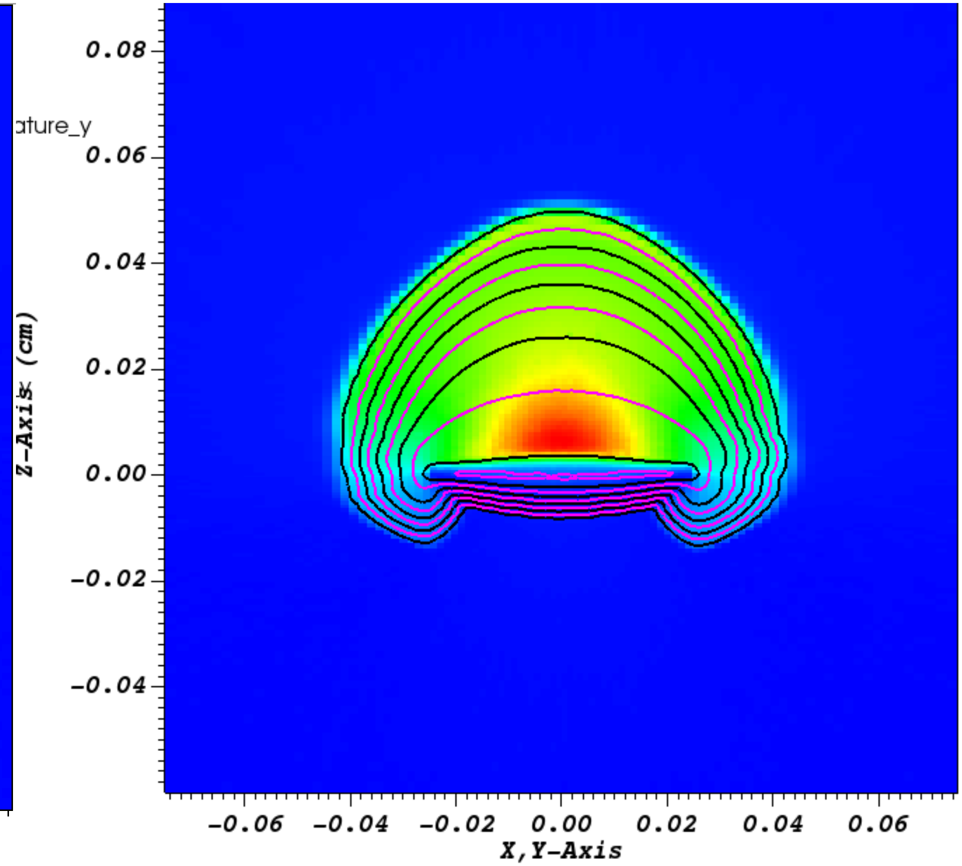


Temperature and electron density profiles at 10 ns before maximum of laser power

y = 0 cross-section, Te_max = 42 eV



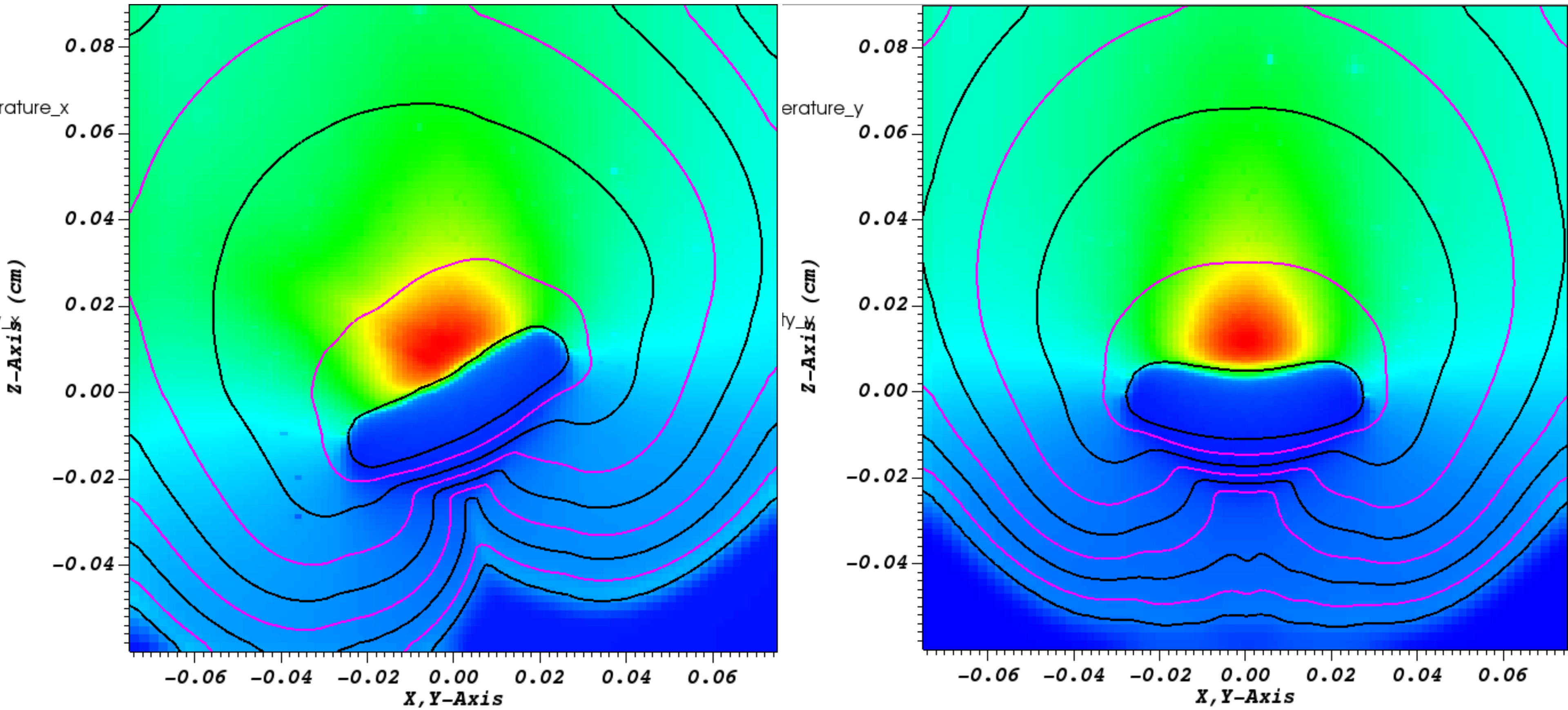
x = 0 cross-section



1. Lines of equal density are shown (1 order difference between neighboring lines)
2. **Laser plum is expending mainly normal to target surface**
3. Still small asymmetry is seen in plasma temperature and plasma expansion behind disk

Temperature and electron density profiles at maximum of laser power

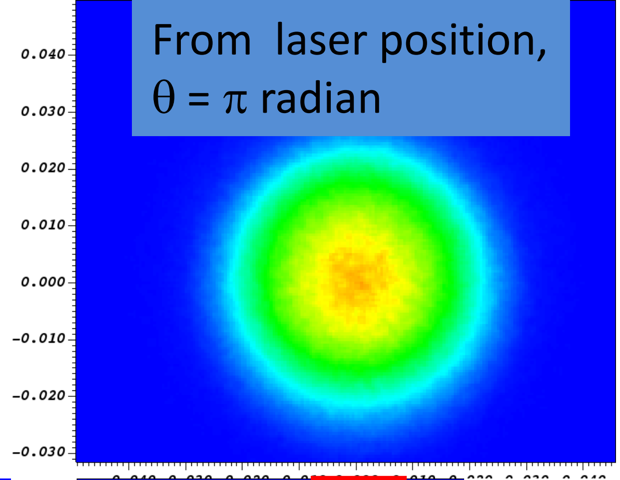
y = 0 cross-section **Te_max = 87 eV** **x = 0 cross-section**

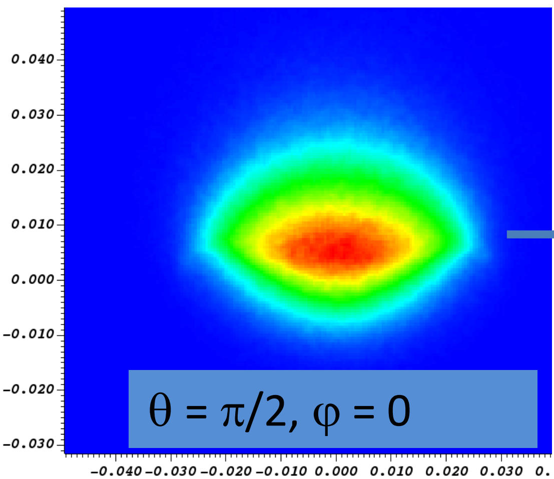


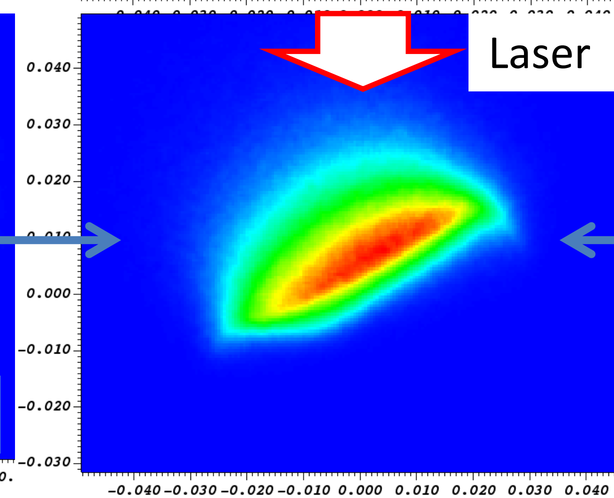
1. Main output of the task:
   - Angle and velocity distribution of plasma flows
   - Full distribution function of emitted EUV-UV radiation:
     $f(t,x,y,z,\theta,\varphi,\lambda)$, were θ and φ are polar and azimuth angles of emitted radiation

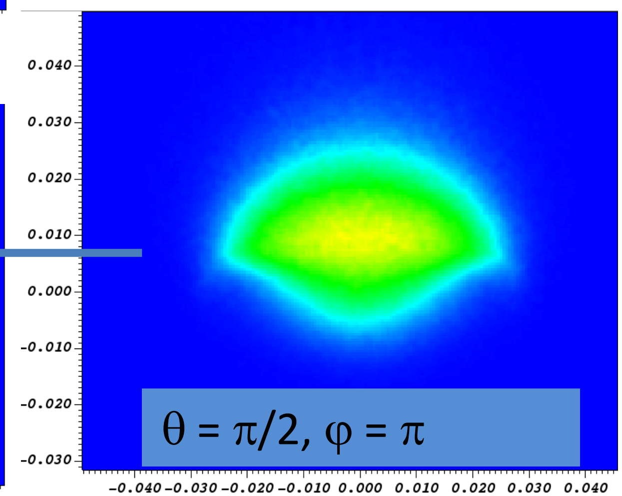
EUV images

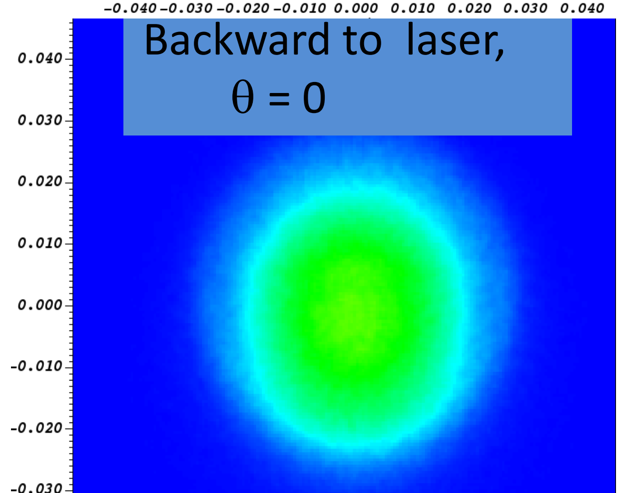
Images were integrated over 150 ns of modeling time











φ = 0 image is more bright then φ = π due to absence of dense plasma from initial target in this direction

function f(t,x,y,z,θ,φ,λ) can also be used for modeling of EUV images in optical system by ray tracing method since it initially presented as set of photons leaving modeling region

Conclusion

- Possible optimal wavelengths for EUV sources of different size and laser energy in one pulse are given
  - 5 (or 10) um wavelength is optimal at large laser energy (0.2 J; 10 ns)
  - 2 (or 5) um wavelengths are optimal at small laser energy (0.01 J; 10 ns)
- Radiation hydrodynamic simulations of $\lambda = 2$ μm irradiation of tin micro-droplets were done: laser energy 0.004 – 0.040 J; duration 10 ns; 25 – 50 um droplet
- Doppler effect should be taken into account at modeling of LPP EUV sources. It needs more or about 20 000 wavelength groups during modeling
- 3D modeling of HVM LPP EUV source was done on personal computer. Several EUV images were constructed which shows, that EUV source is optically thick