# Ion energy distributions of Sn laser-produced plasmas

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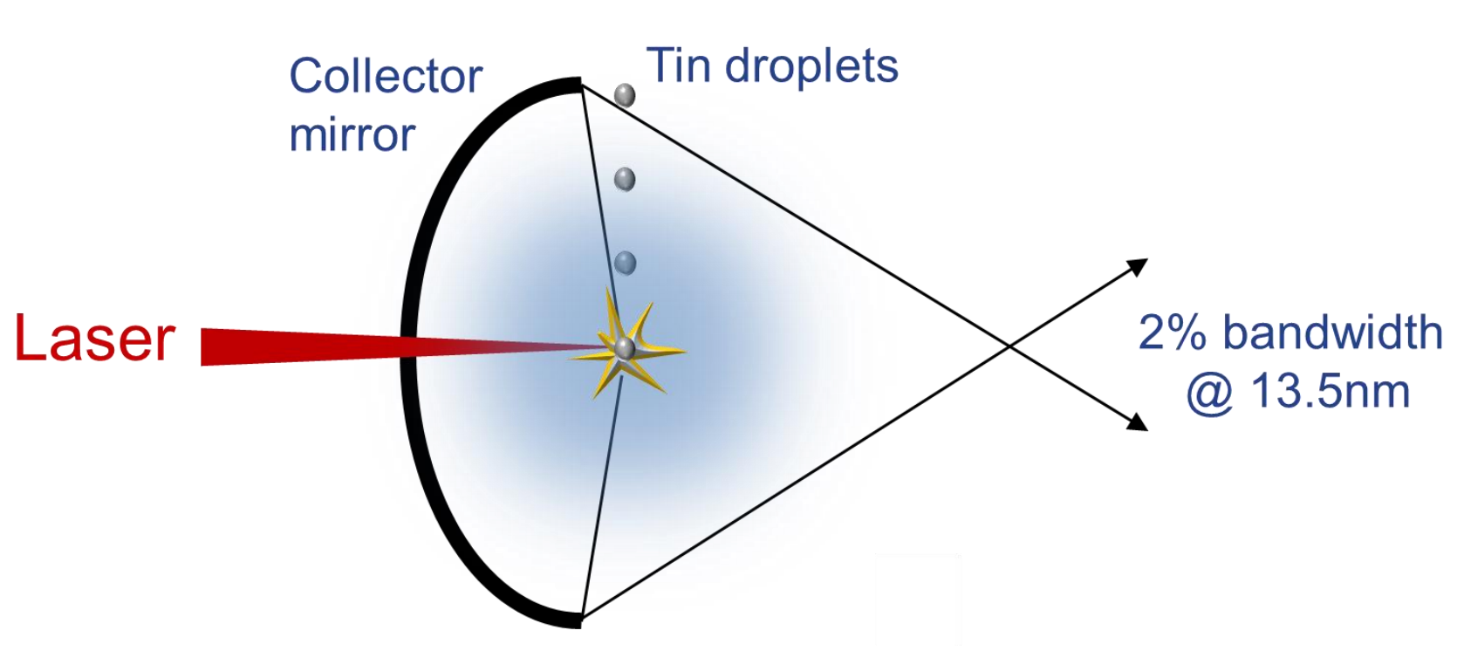
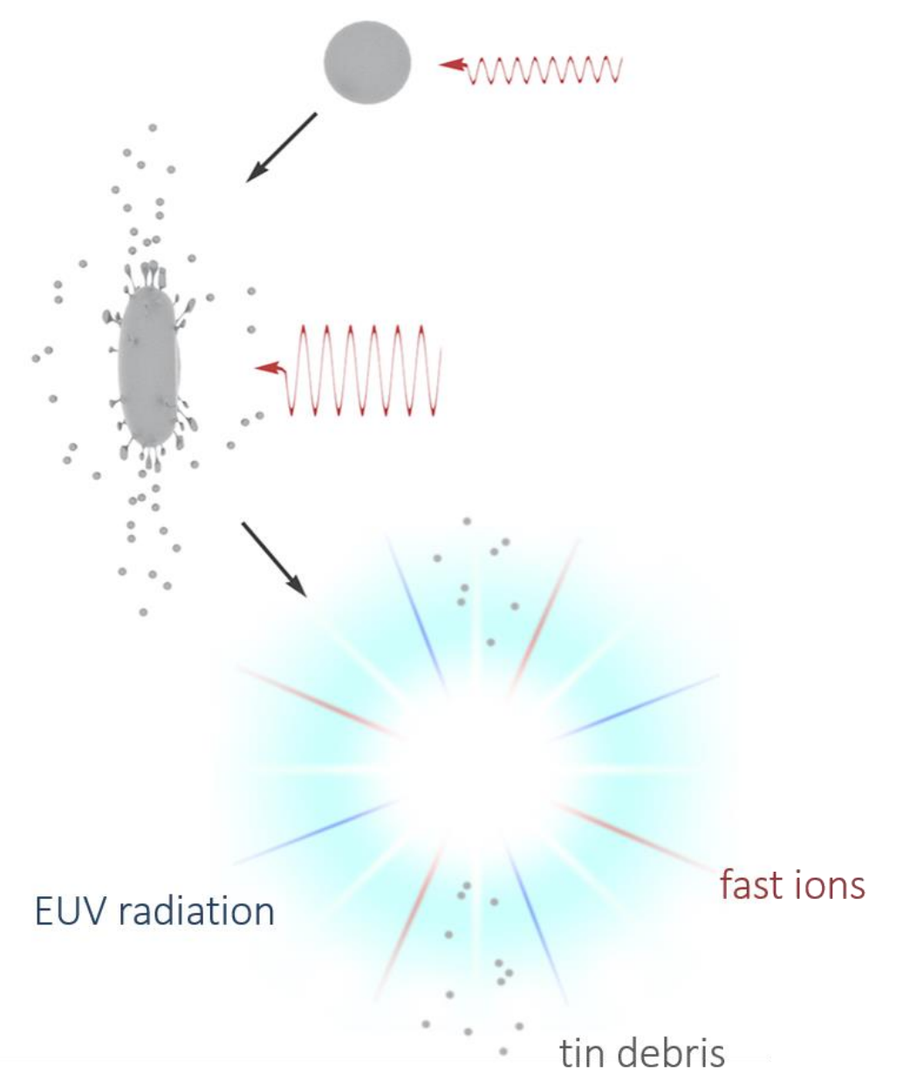


New-generation nanolithography machines employ extreme ultraviolet (EUV) light to enable patterning of nm-scale features. EUV light (13.5 nm ± 1%) is produced efficiently by de-excitation of highly charged tin ions in a hot and dense laser-produced plasma (LPP). However plasma expansion into a high-vacuum nanolithography machine leads to contamination of its main EUV collector mirror. [1]

The following study aims to provide an understanding of tin plasma expansion and the possible mitigation of its most damaging components. Hereafter we present a preliminary comparison between ion energy distributions measured experimentally and simulated with the radiation-hydrodynamics code RALEF-2D.



## Measurement of ion energy spectra

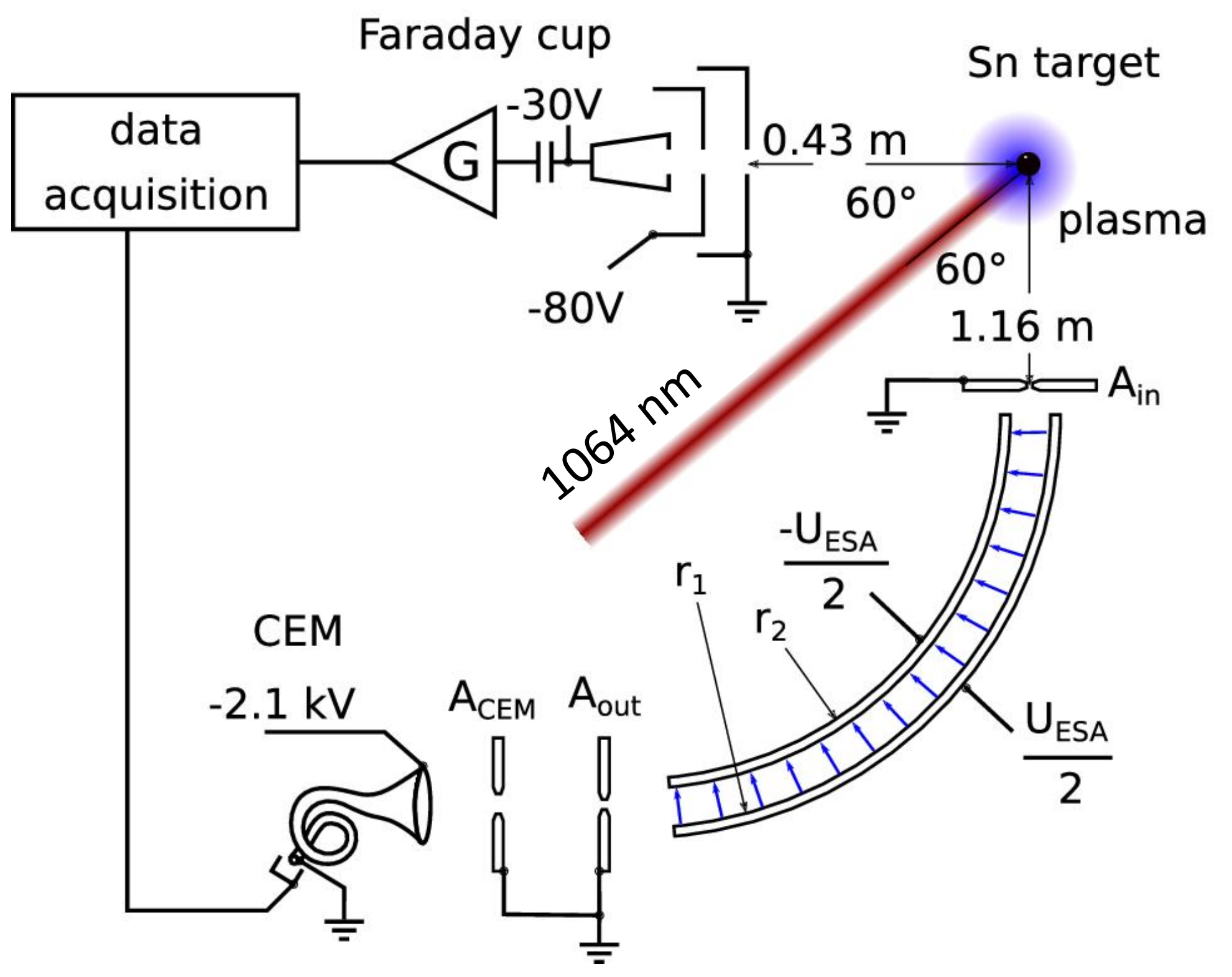


*Figure 1: Plasma ion detection setup with one Faraday cup and an electrostatic analyzer.*

### Faraday cup

- Time-of-flight (TOF) ion spectrometer:
$$E = \frac{1}{2}m(L_{TOF}/TOF)^2$$
- $dQ(E)/dE$ is derived from ion current $I(E)$

### Electrostatic analyzer (ESA)

- Ion energy filter and TOF spectrometer :
$$E_Z(U_{\mathrm{ESA}}) = \frac{eZU_{\mathrm{ESA}}}{2ln(r_1/r_2)}$$
- Peak finding in $V_{CEM}(t)$ gives TOF and $Z$ for each ion
- $Z$ resolved up to $Z = 8$
- $d\mathrm{N}_Z(E)/dE$ obtained
- $\sum_Z dQ_Z(E)/dE = \sum_Z Z \times d\mathrm{N}_Z(E)/dE \approx dQ(E)/dE$

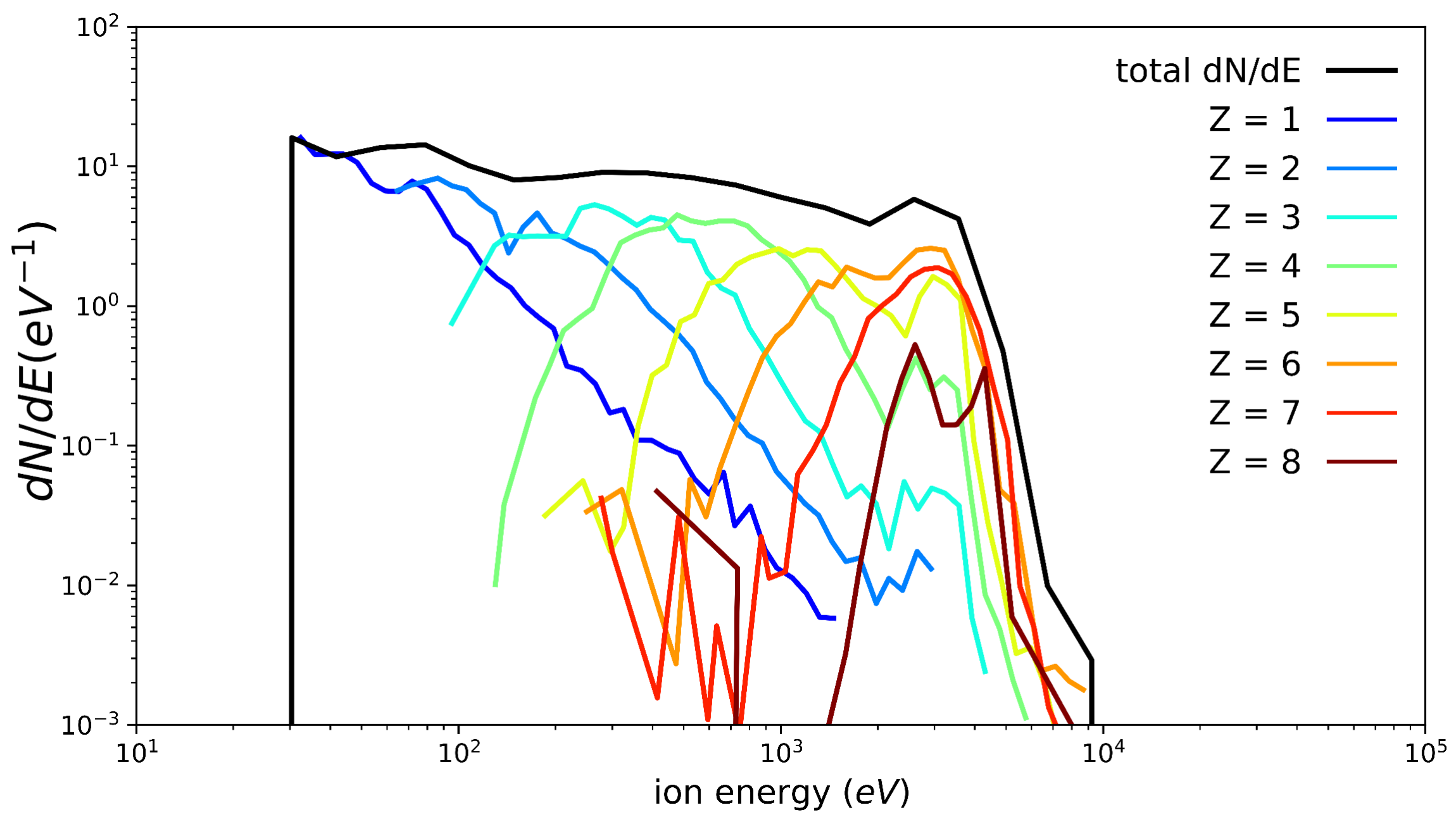


*Figure 2: State-charge-resolved tin ion energy distribution as measured by the ESA; colored solid lines account for the spectra of individual charge-states $dQ_Z(E)/dE$ and the black solid line is their sum $dQ(E)/dE$; in this experiment a 30 µm tin droplet was hit by a 300 mJ, 7 ns FWHM laser pulse from a Nd:YAG laser (1064 nm) in ultra-high vacuum.*

## Comparison between experiment and simulation

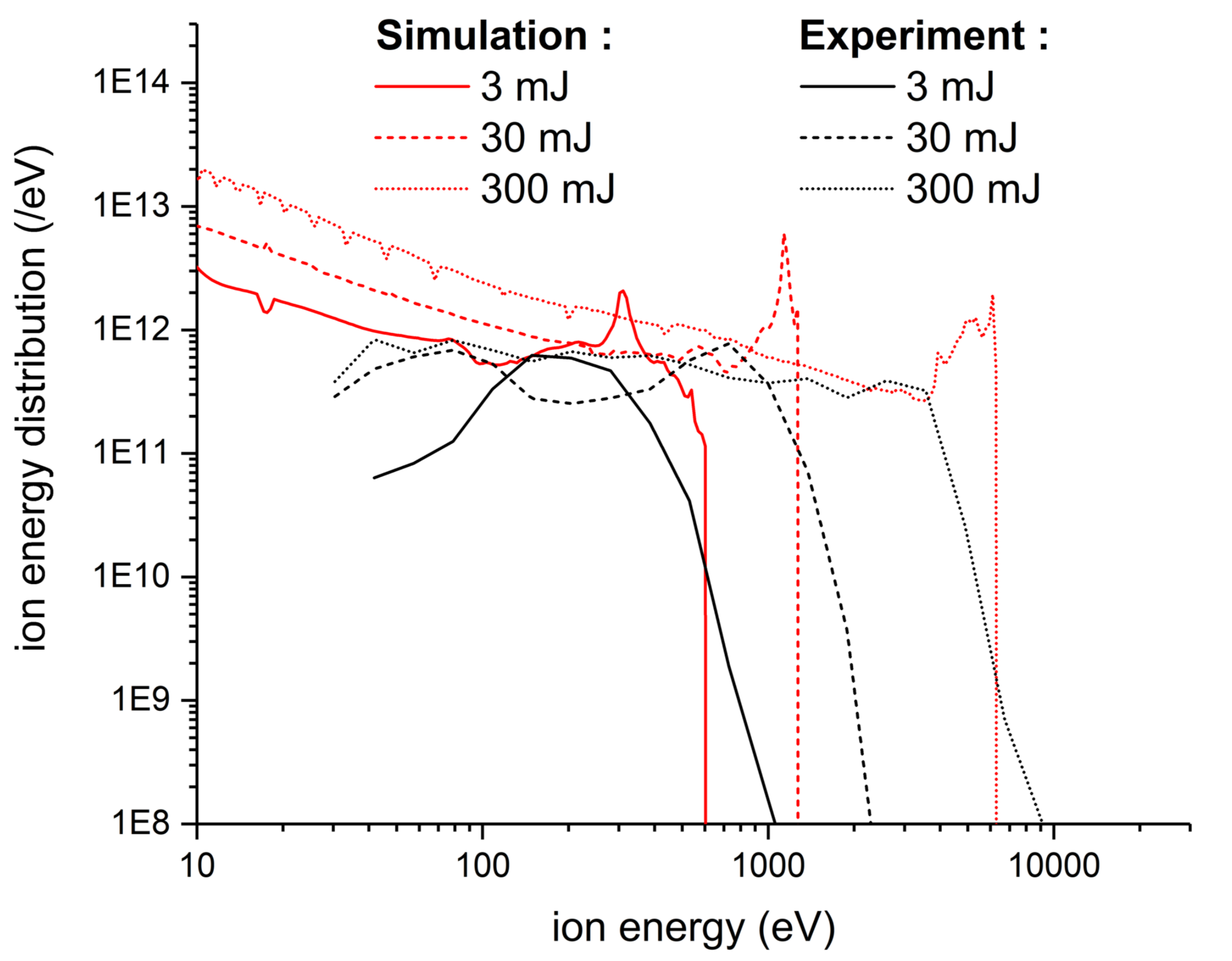


*Figure 5: Ion energy distribution at 60° with respect to the laser axis as produced by an* ***experiment*** *(using the ESA) and a RALEF-2D* ***simulation****. Amplitudes of the experimental spectra are normalized at the high-energy shoulder with a common factor to fit the simulation.*

## Simulation with RALEF-2D

### RALEF-2D

- Radiation Arbitrary Lagrangian-Eulerian Fluid dynamics in 2 Dimensions [3]
- Includes heat conduction and radiation transport

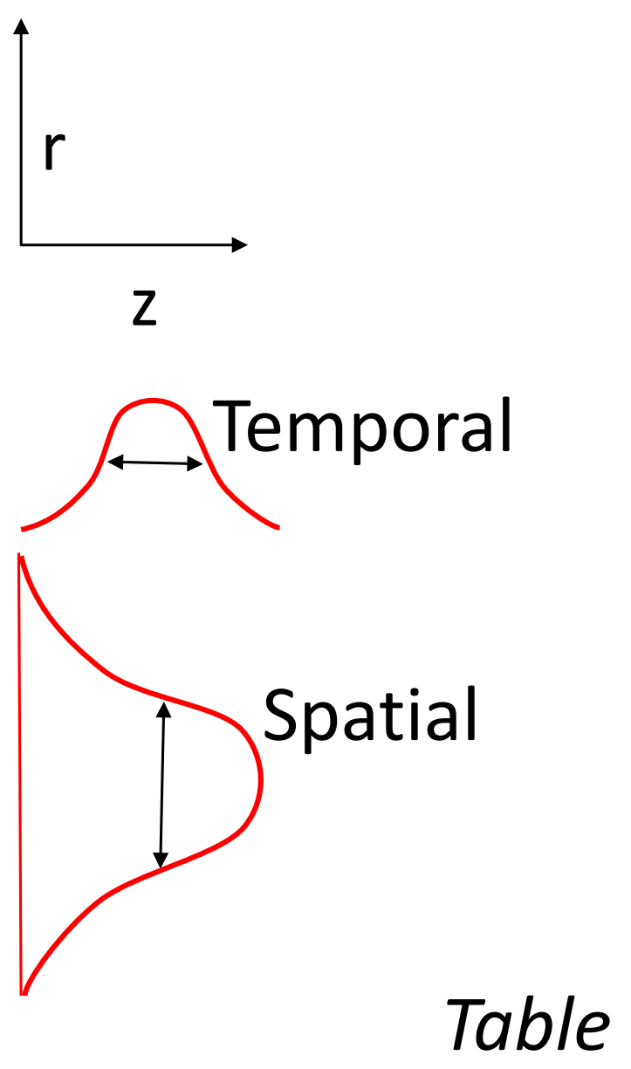


*Figure 3: Crude version of computational mesh*

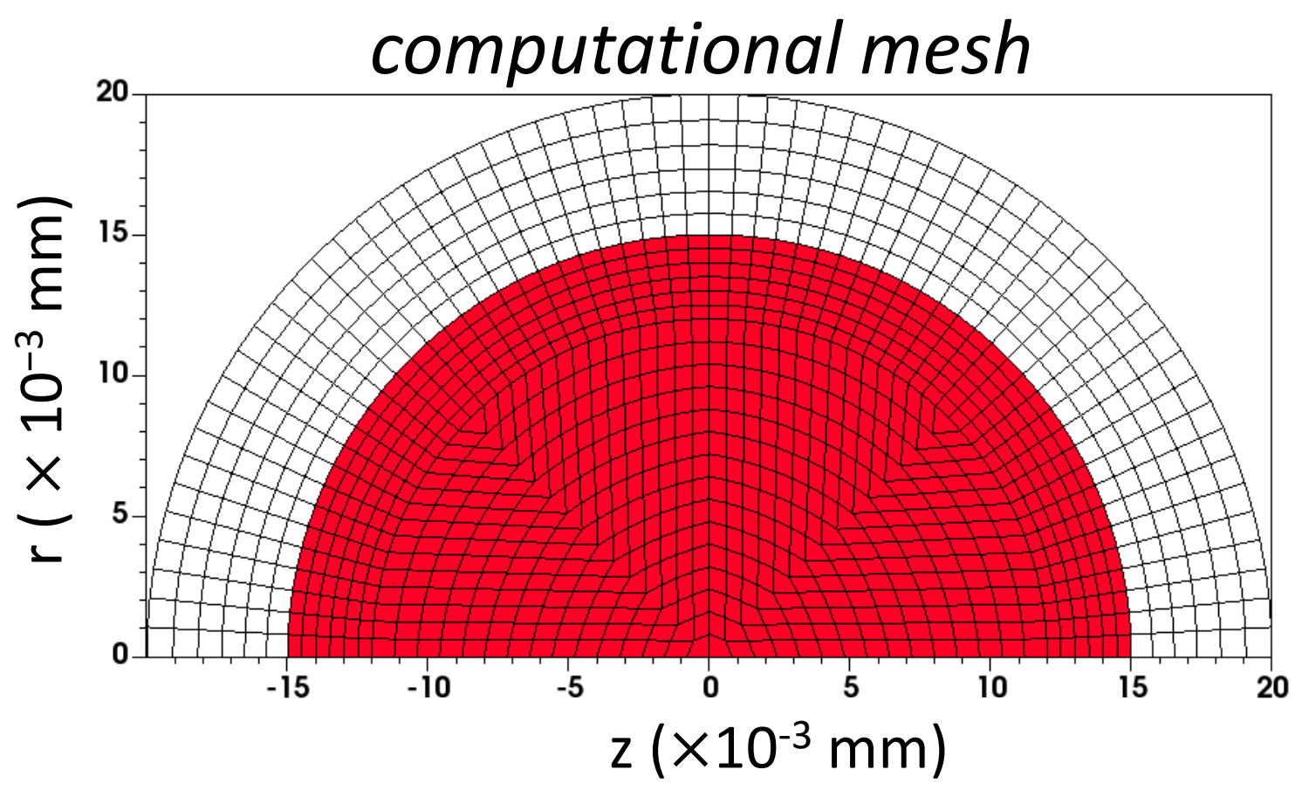


*Table 1: Simulation parameters*

| | |
|---|---|
| Droplet diameter | 30 µm |
| Spatial laser profile | Gaussian 105 µm FWHM |
| Temporal laser profile | Gaussian 7 ns FWHM |
| Laser pulse energy | Ranging from 3 to 300 mJ |
| Laser wavelength | 1064 nm |
| Radius mesh boundary | 1 mm |

### Ion distribution output

- Energy- and angle-resolved ion distributions
- Based on mass density and velocity field
- Records number of particles leaving the mesh

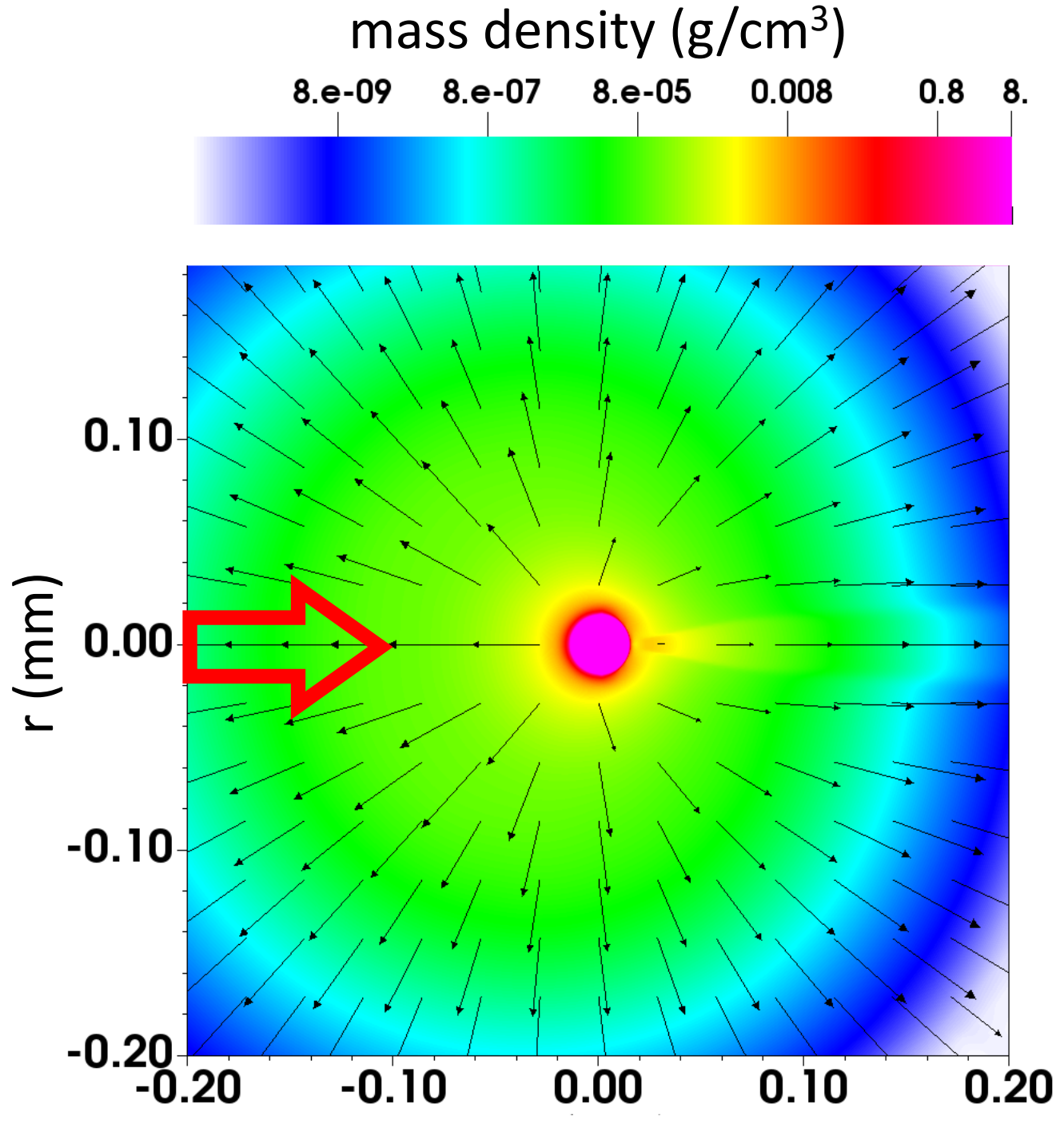


*Figure 4: Mass density (g/cm$^3$, logarithmic scale) and velocity field 10 ns after the start of the simulation; the red arrow indicates laser direction.*

### Assumptions

- Non-refractive model
- Not charge-resolved
- Plasma as quasi-neutral hot gas
- Single-fluid approximation
- No surface tension

## Conclusion

- ✓ Similar trends in measured and simulated dN/dE(E)
- ✓ Sharp cutoff at high energy
- ✓ Linear flat trend at low energy
- ✓ Similar increase of cutoff position with increasing laser energy

- x Shoulder smoothness not reproduced by the simulation
- x Overestimation of plasma temperature in RALEF-2D (?)

## References

[1] O. O. Versolato, *Plasma Sources Sci. Tech.*, ***28***, 083001, 2019
[2] A. Bayerle, et al., *Plasma Sources Sci. Technol.* **27**, 045001, 2018
[3] M.M. Basko, J. Maruhn and A. Tauschwitz, *RALEF main report*, 2017