A few remarks on EUVL data analysis

Alexander Grushin, Ilia Vichev, Dmitrii Kim, Anna Solomyannaya

Keldysh Institute of Applied Mathematics RAS, Moscow, 125047 Russia

grushina@kiam.ru
annads@kiam.ru
vichevilya@keldysh.ru
kimda@kiam.ru

General speculations

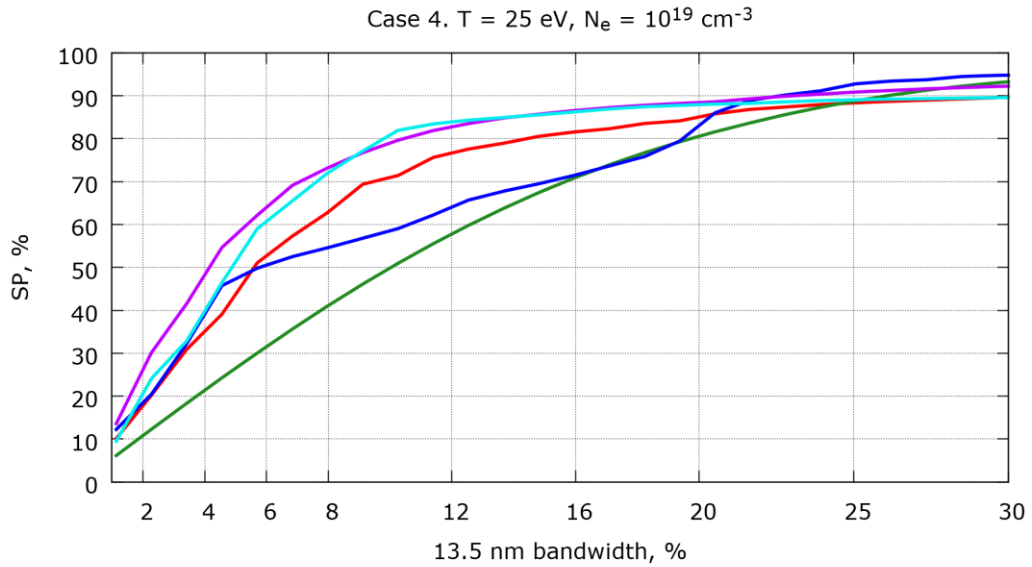
- The 13.5 nm ± 1% bandwidth is an extremely stiff condition to comply – even slightest deviation of a simulated spectral line from “true” position can result in its skipping out of the 2% window and decrease the accountable EUV emission.
- Another vital factors are the spectral lines shape and width, which are still a hot topic to discuss. Both of these can somewhat influence the amount of energy in 2% bandwidth.
- Due to vast amount of spectral lines in tin plasma at the vicinity of 13.5 nm wavelength, the detailed spectra accounting is very expensive and some simplifications (averaging techniques, mixing DCA-UTA approach, etc.) are usually applied. And this in turn widens the spectra even more, thus decreasing the spectral purity and predicted conversion efficiency and power output of the modelled EUV source.
- To conclude: the 2% bandwidth and its derivatives are more of engineering and experimental quantities.

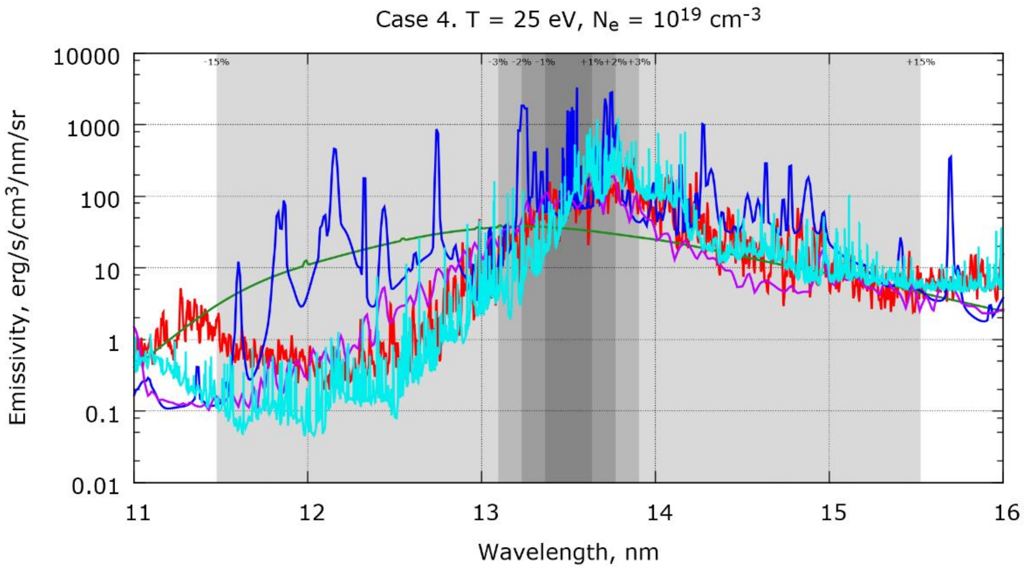
Suggestions

- Not discarding the significance of having correct atomic data, the first thing, that comes to mind – arrange a direct comparison of the tin atomic data (computer aided or via some form of averaging or some other way).
- For now shift the focus from comparing the engineering characteristics ($CE_{2\%}$, $SP_{2\%}$, $EUV_{2\%}$ power output) of the simulated EUV source towards some other quantities. For example, instead of searching for the maximum $SP_{2\%}$ or $CE_{2\%}$, predict plasma parameters, where the SP or CE are maximal, and compare these parameters (T, Ne, mean charge and charge distribution, etc.).

$$\text{SP} = 100\% \times \frac{\int_{13.5-\Delta l}^{13.5+\Delta l} \eta_\lambda d\lambda}{\int_0^\infty \eta_\lambda d\lambda}$$

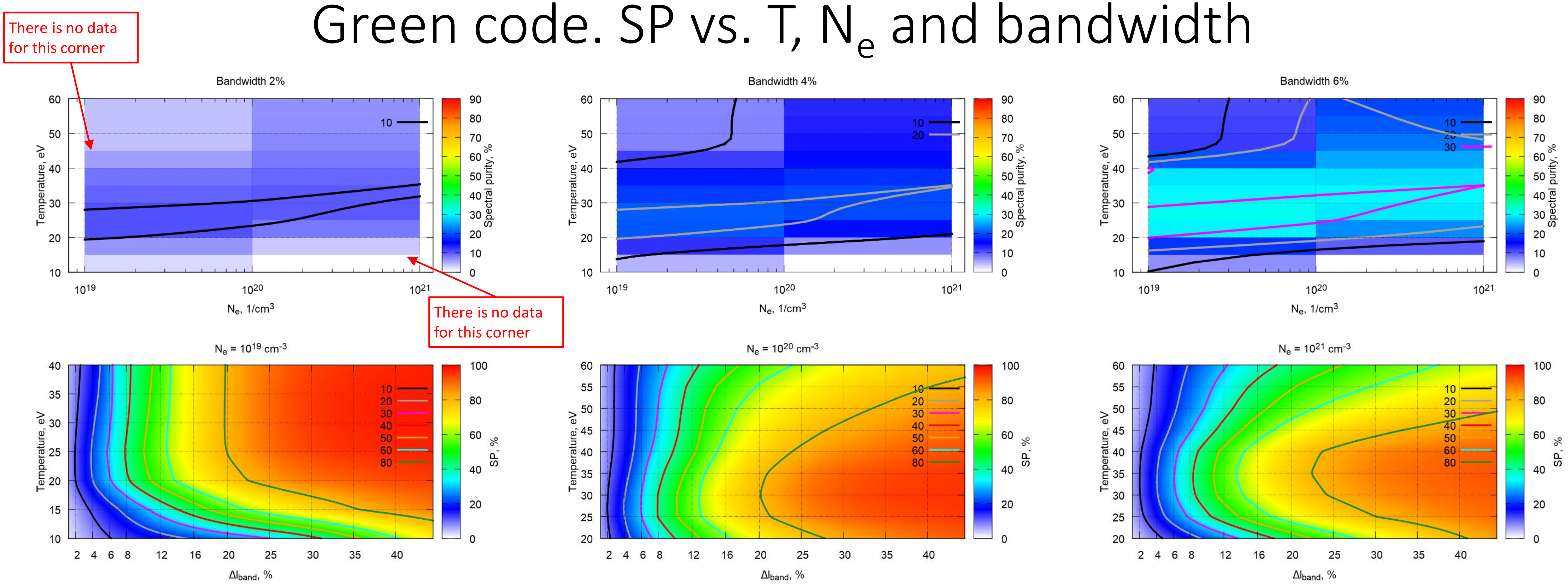
SP over wide window





- If we fix the bandwidth at let’s say 2%, we get quite a dispersion of SP varying from 10% up to almost 30%.
- Fixing the SP however makes results a lot closer to each other (except the green code) for up to 5% bandwidth.

Green code. SP vs. T, N_e and bandwidth



Two slightly different approaches to estimating the most optimal plasma parameters:

- Top row – analyze SP for different bandwidths over T and N_e (results are rather crude due to sparse and incomplete grid for T and N_e).
- Bottom row – analyze SP for different N_e over T and bandwidth.

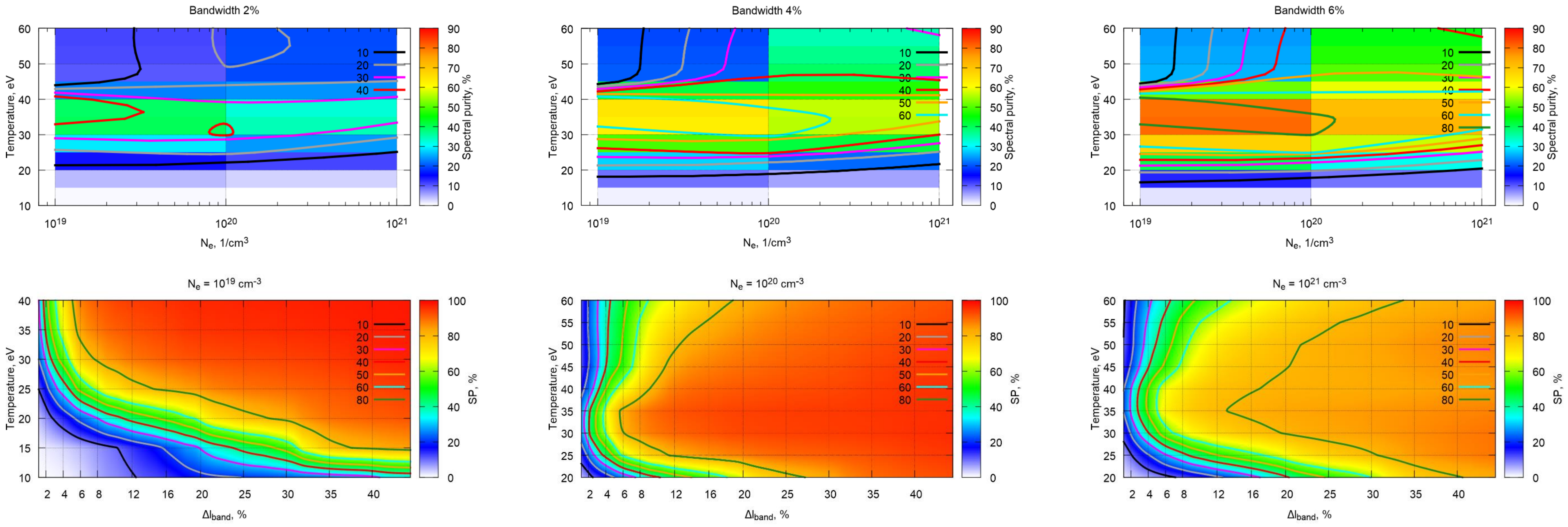
Both bring similar results →

Optimal plasma parameters (from SP point of view):

- T = 20 – 25 eV for $N_e = 10^{19}$ cm^{-3};
- T = 25 – 30 eV for $N_e = 10^{20}$ cm^{-3};
- T = 30 – 40 eV for $N_e = 10^{21}$ cm^{-3}.

Varying the bandwidth ensures that the stability of observed optimal parameters.

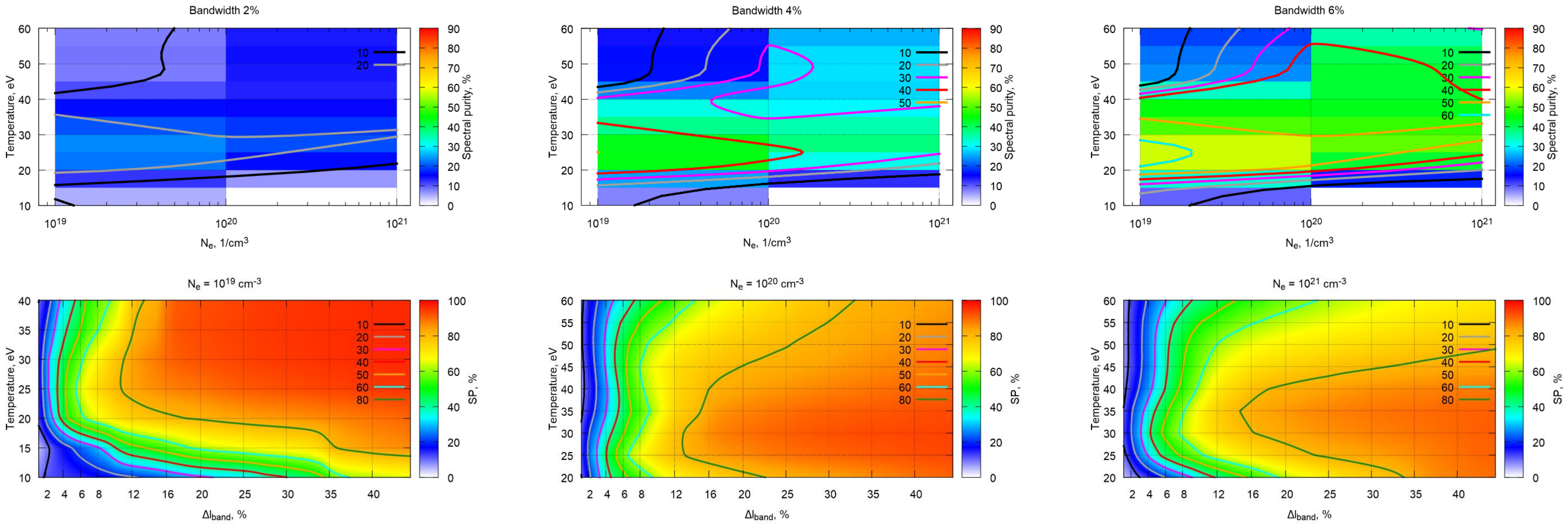
Red code. SP vs. T, N_e and bandwidth



Optimal plasma parameters (from SP point of view):

- T > 40 eV for $N_e = 10^{19}$ cm^{-3};
- T = 30 – 35 eV for $N_e = 10^{20}$ cm^{-3};
- T = 35 – 40 eV for $N_e = 10^{21}$ cm^{-3}.

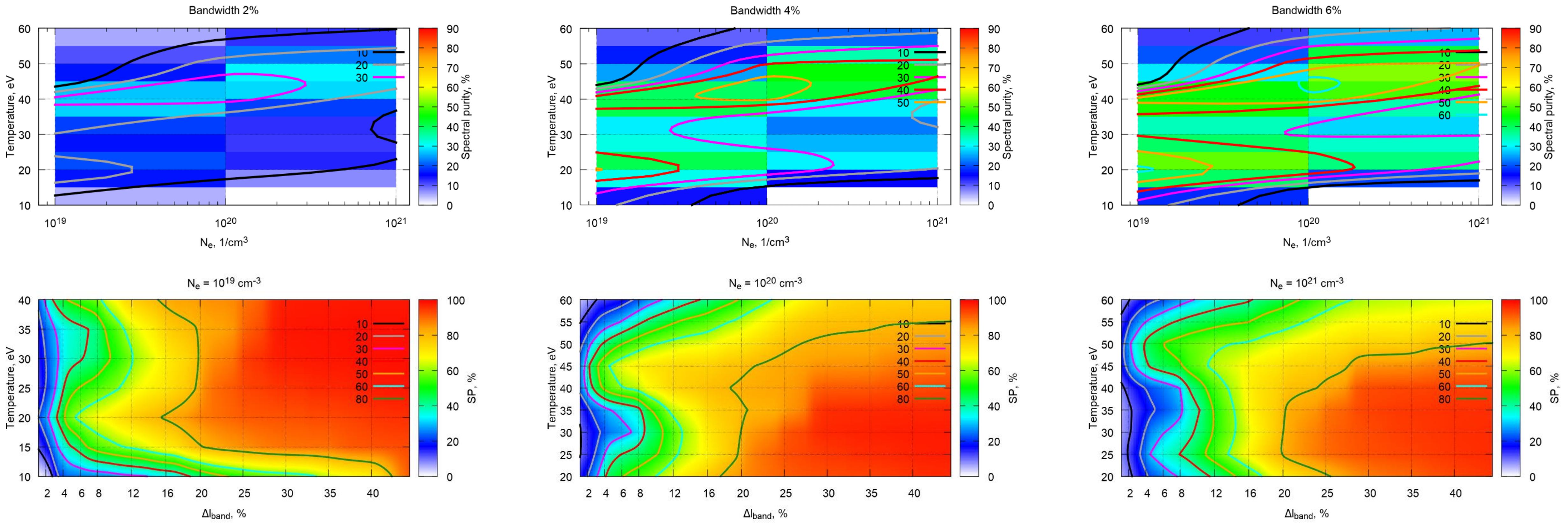
Magenta code. SP vs. T, N_e and bandwidth



Optimal plasma parameters (from SP point of view):

- T = 20 – 30 eV for $N_e = 10^{19}$ cm^{-3};
- T = 25 – 30 eV for $N_e = 10^{20}$ cm^{-3};
- T = 30 – 35 eV for $N_e = 10^{21}$ cm^{-3}.

Blue code. SP vs. T, N_e and bandwidth

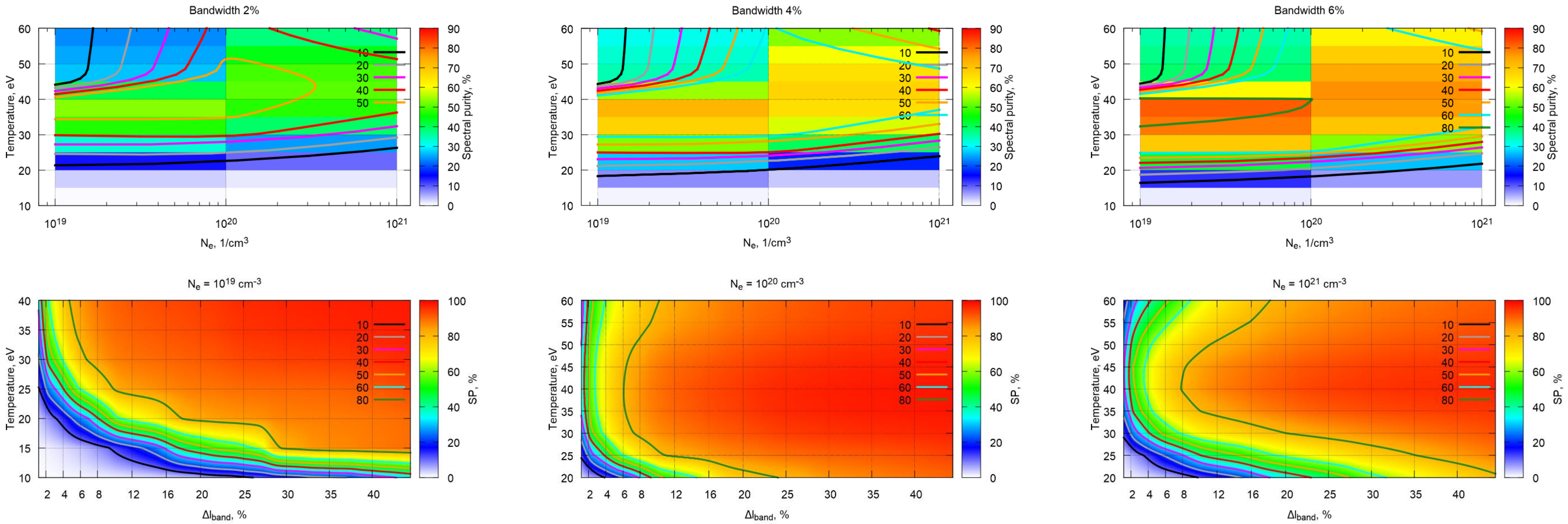


These results are rather tricky to analyze due to non-monotonous behavior of SP.

Optimal plasma parameters (from SP point of view):

- T = 20 eV; > 40 eV for $N_e = 10^{19}$ cm^{-3};
- T < 20 eV; 40 – 45 eV for $N_e = 10^{20}$ cm^{-3};
- T = 25 eV; 45 – 50 eV for $N_e = 10^{21}$ cm^{-3}.

Cyan code. SP vs. T, N_e and bandwidth



Optimal plasma parameters (from SP point of view):

- T > 40 eV for $N_e = 10^{19}$ cm^{-3};
- T = 35 – 45 eV for $N_e = 10^{20}$ cm^{-3};
- T = 35 – 45 eV for $N_e = 10^{21}$ cm^{-3}.

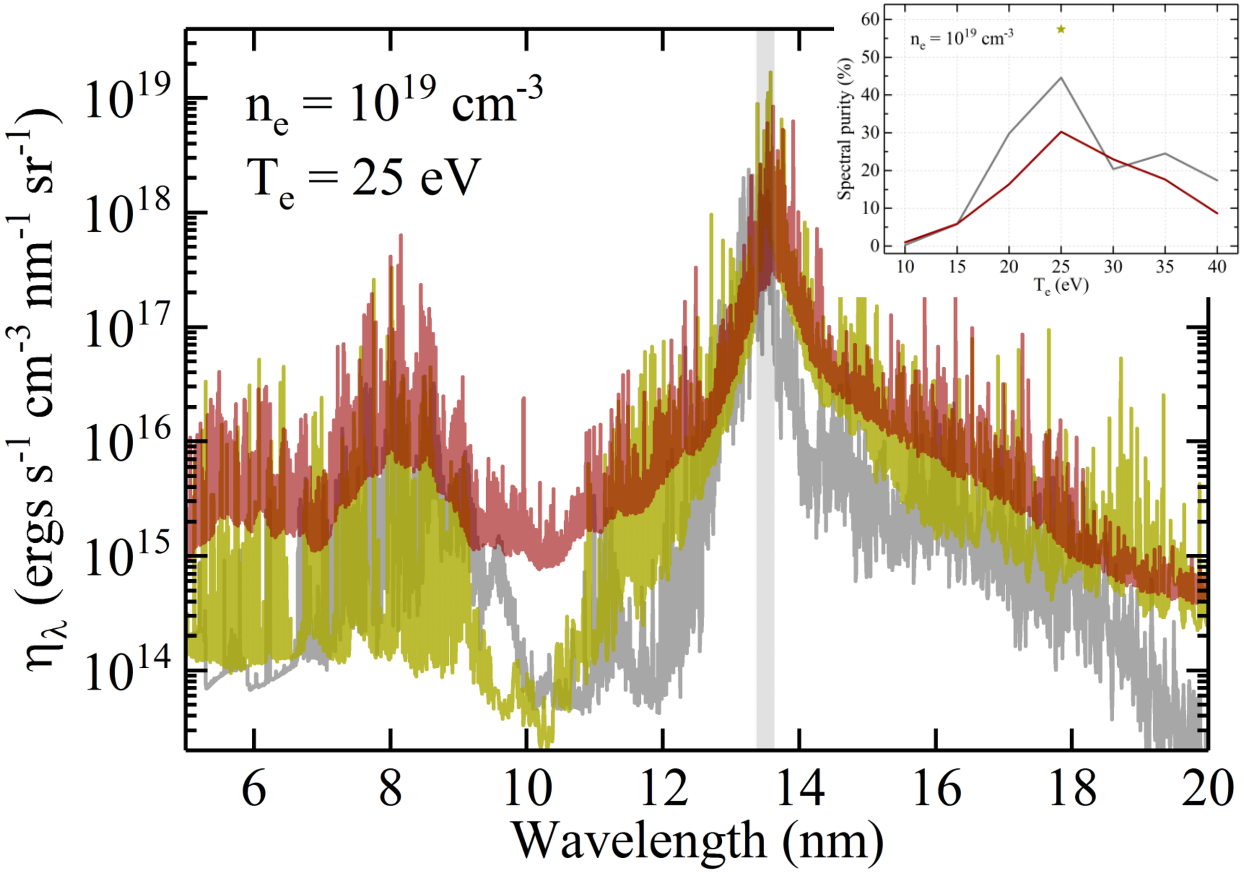
Optimal plasma parameters

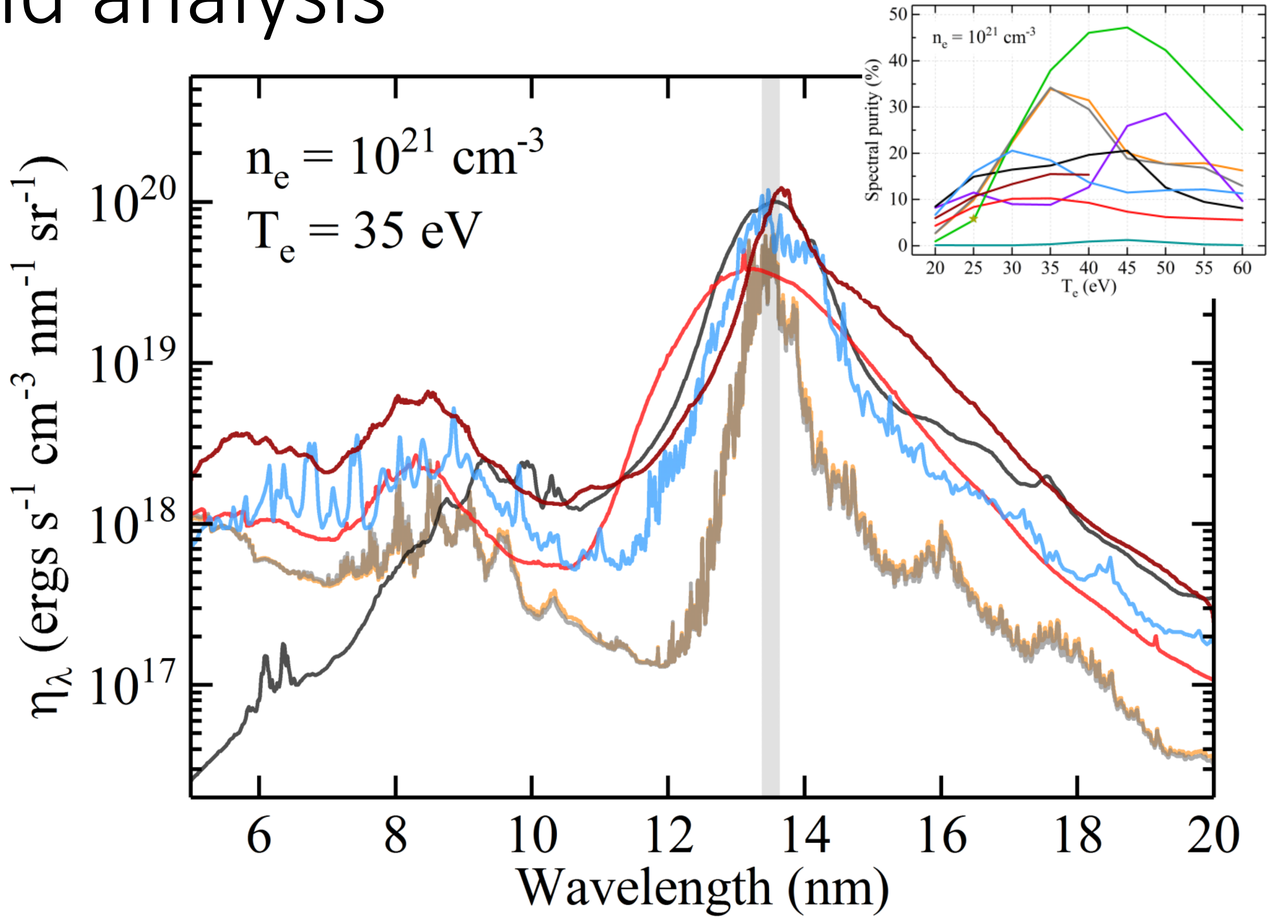
Code	$N_e = 10^{19}$ cm^{-3}	$N_e = 10^{20}$ cm^{-3}	$N_e = 10^{21}$ cm^{-3}
Green	20 – 25 eV	25 – 30 eV	30 – 40 eV
Red	> 40 eV	30 – 35 eV	35 – 40 eV
Magenta	20 – 30 eV	25 – 30 eV	30 – 35 eV
Blue	20 eV > 40 eV	< 20 eV 40 – 45 eV	25 eV 45 – 50 eV
Cyan	> 40 eV	35 – 45 eV	35 – 45 eV

At electron densities 10^{19} cm^{-3} – 10^{20} cm^{-3} the codes demonstrate noticeable discrepancies in the results.

One can say with decent degree of confidence, that at high density the codes reach an agreement.

Out-of-band analysis





Reviewing the spectral plots one cannot help but notice the intense shortwave background spectrum for the brown colored code results.

This is probably the result of taking into account the high-lying configurations within the Sn^{8+} – Sn^{15+} ions [1].

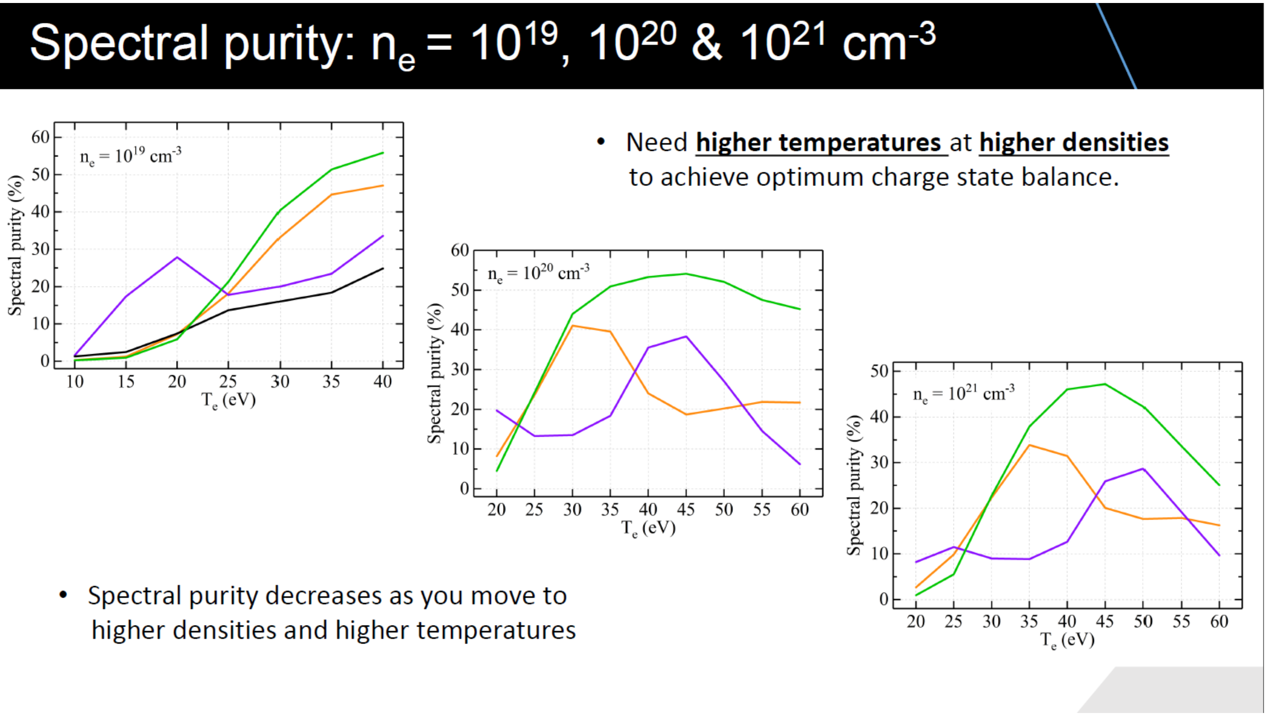
And it is also one of the reasons why the brown code has one of the lowest SP. The statements made in [1] seem to be important enough to be investigated on the next EUVL session.

[1] F. Torretti *et al.*, "Short-wavelength out-of-band EUV emission from Sn laser-produced plasma," *Journal of Physics B: Atomic, Molecular and Optical Physics*, vol. 51, no. 4, p. 045005, Feb. 2018, DOI:10.1088/1361-6455/aaa593.

Detailed data analysis

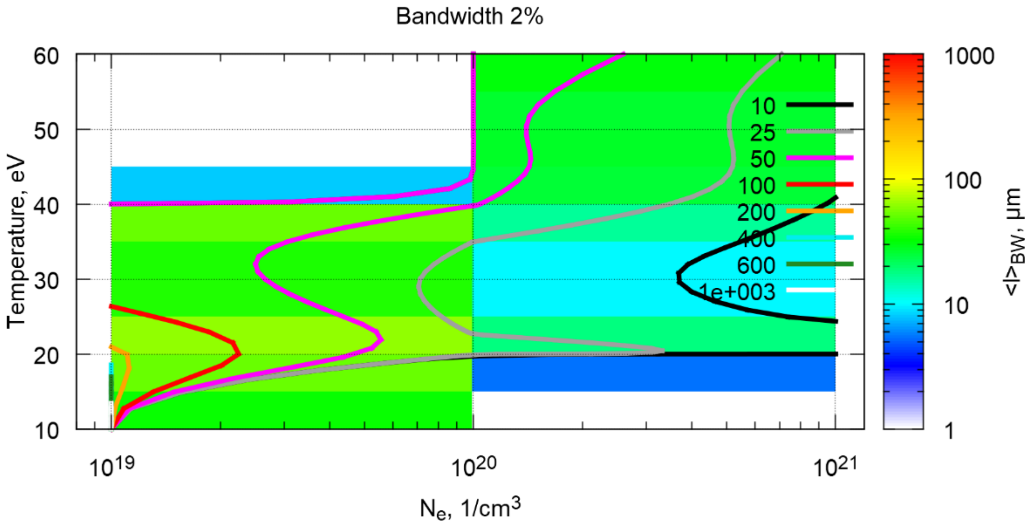
- Expand the set of quantities for comparison to NLTE workshop standard. Maybe even transform this session into a spin-off NLTE-seminar with regard to EUV specifics.
- Comparison with experimental spectra.

Observations

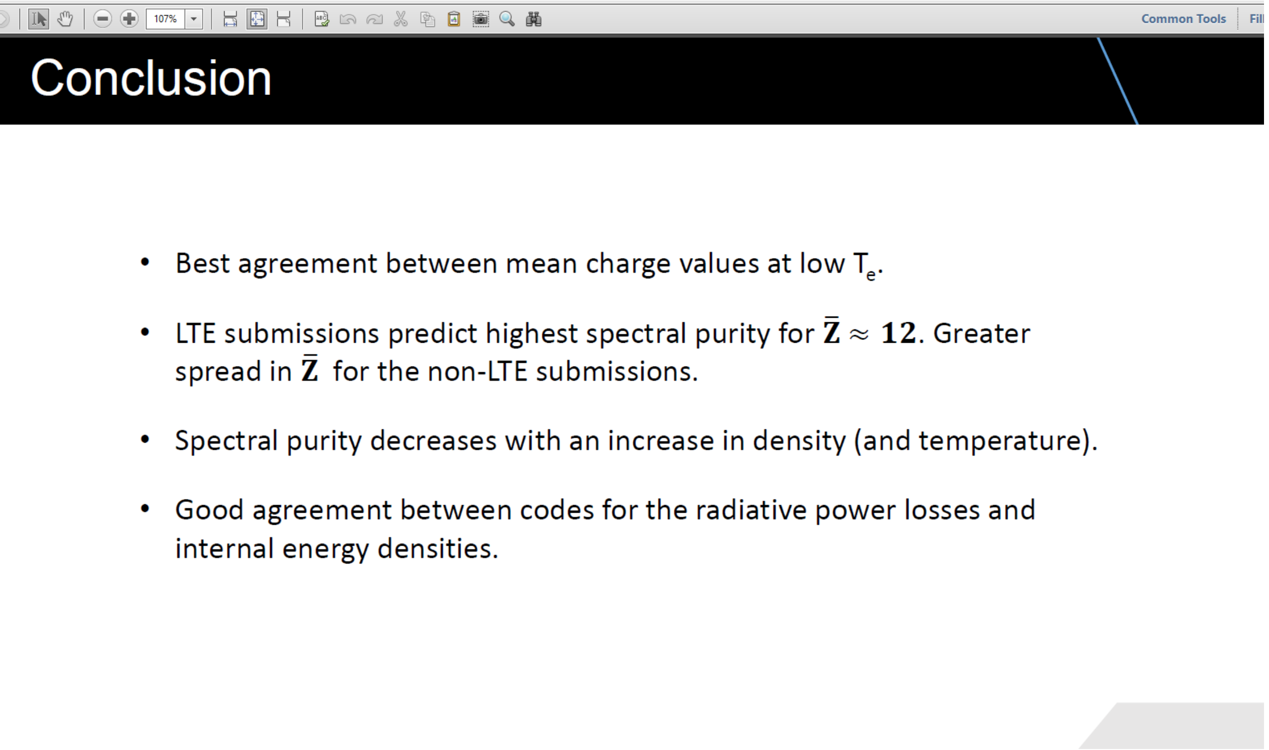


Don't these two statements contradict each other?

- Statements on this slide aren't entirely correct:
  - There seem to be optimal temperature and density region, where the SP reaches its' top values.
  - One should also take into consideration the attenuation length, which gives information about reabsorption of the emitted EUV radiation.



Conclusions



- The main difference between the codes so far lies in the atomic data used.