Photon-assisted transport and gain clamping

Photon-assisted transport

Photon-assisted transport can be modeled by considering electromagnetic (EM) modes at specific energies.

```
<EMfield>
<EMmode>
<PhotonEnergy unit="mV">253.0</PhotonEnergy>
</EMmode>
</EMfield>
```

Note that in the current version (2020-11-16), only a single EM mode is supported at a time.

The electric field in this EM mode can be either imposed (detection mode) or calculated self-consistently (gain clamping).

The detection mode is relevant to study quantum cascade detectors and/or to study the role of photon-assisted transport.

The electric field can be set in the following way:

```
<EMfield>
<EMmode>
<PhotonEnergy unit="mV">253.0</PhotonEnergy>
<ElectricField unit="V.m^-1">1.0e6</ElectricField>
</EMmode>
```

Relation to gain calculation

The gain feature calculates the linear response to an a.c. incoming field. In this case, the d.c. current is not modified. On the other hand, the photon-assisted transport is modeled through the use of a self-energy (self-consistent Born approximation) to describe both absorption and stimulated emission processes, and has an influence on the d.c. transport. In the case of the electron-photon self-energy, a gain is also calculated at the specified EM mode energy. However, the calculated gain slightly differ from the one calculated using linear response, even for small intensities, as broadening effects are not treated within the same approximations in the two cases. This is all the more the case when going to small photon energy (i.e. long wavelengths). Hence this method can produce unreliable results in terahertz devices where broadening effects are comparable to the photon energy.

Gain clamping

Gain clamping is relevant to the simulation of quantum cascade lasers above threshold. Indeed, when the gain surpasses the cavity losses, lasing starts and the gain is clamped to the cavity losses.

To simulate gain clamping, the following command should be used:

```
    <Gain>
       ...
       <Cavity_Losses unit="cm^{-1}">2.76</Cavity_Losses>
       <GainClamping>yes</GainClamping>
    </Gain>
```

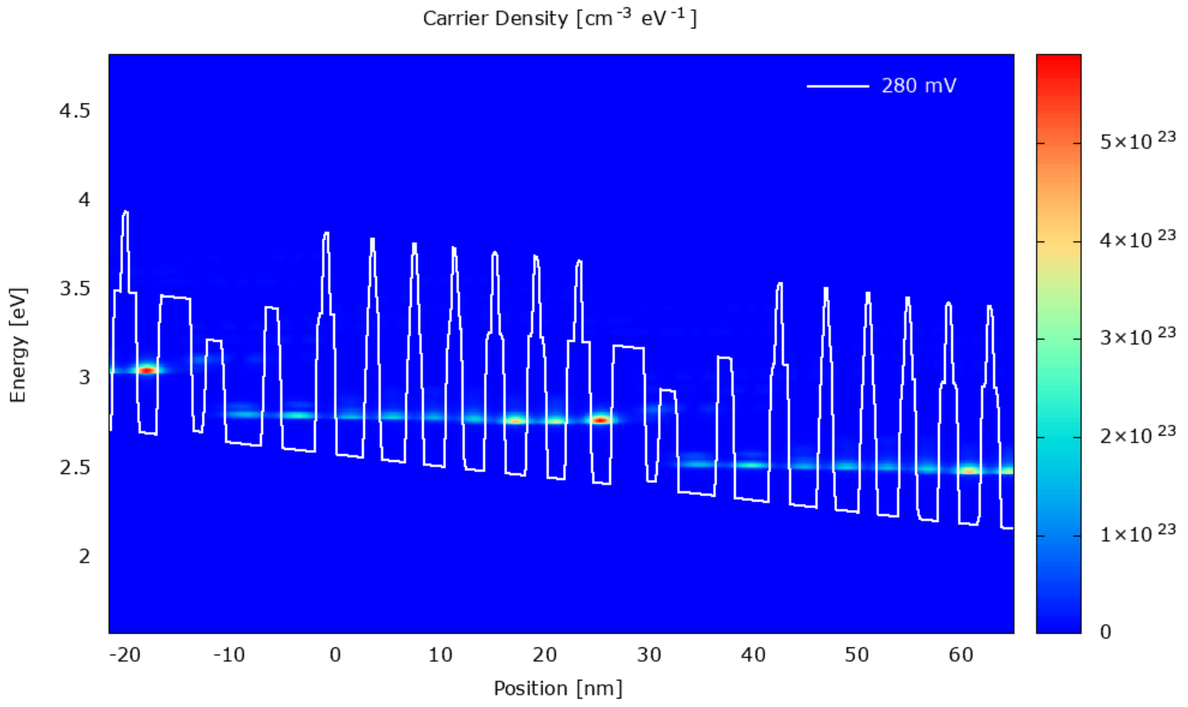
Note that in this case, the EM electric field should be set to zero:

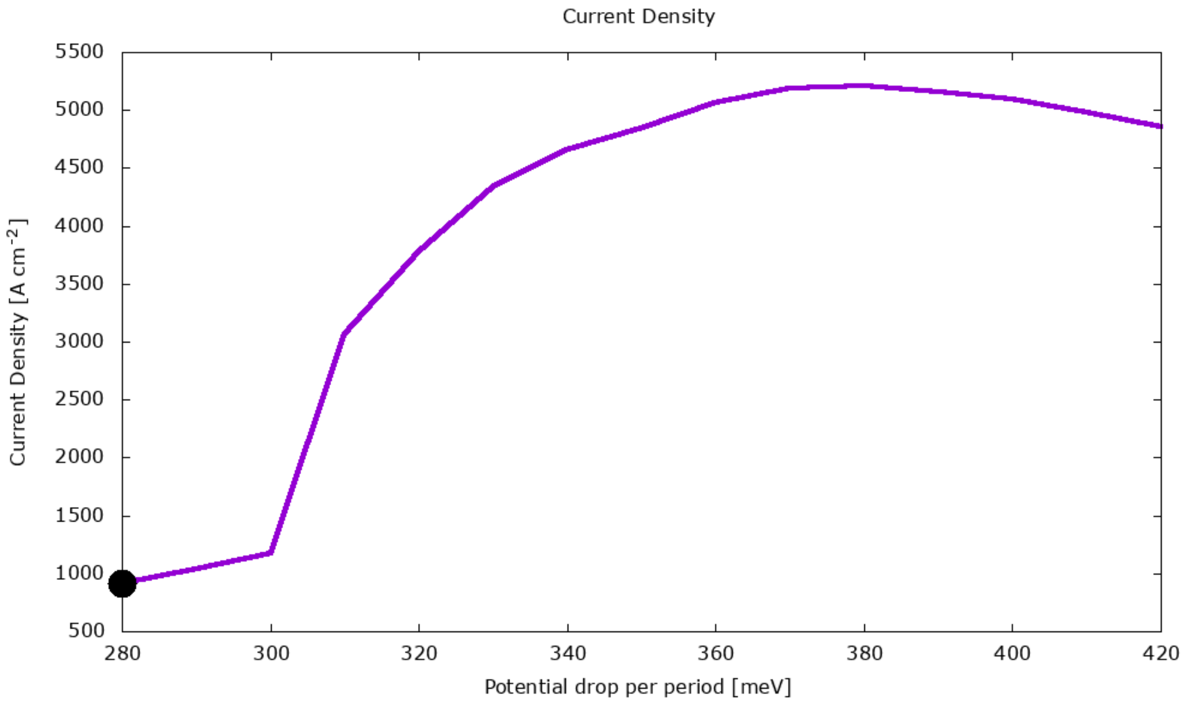
```
<EMfield>
<EMmode>
<PhotonEnergy unit="mV">253.0</PhotonEnergy>
<ElectricField unit="V.m^-1">0.0</ElectricField>
</EMmode>
```

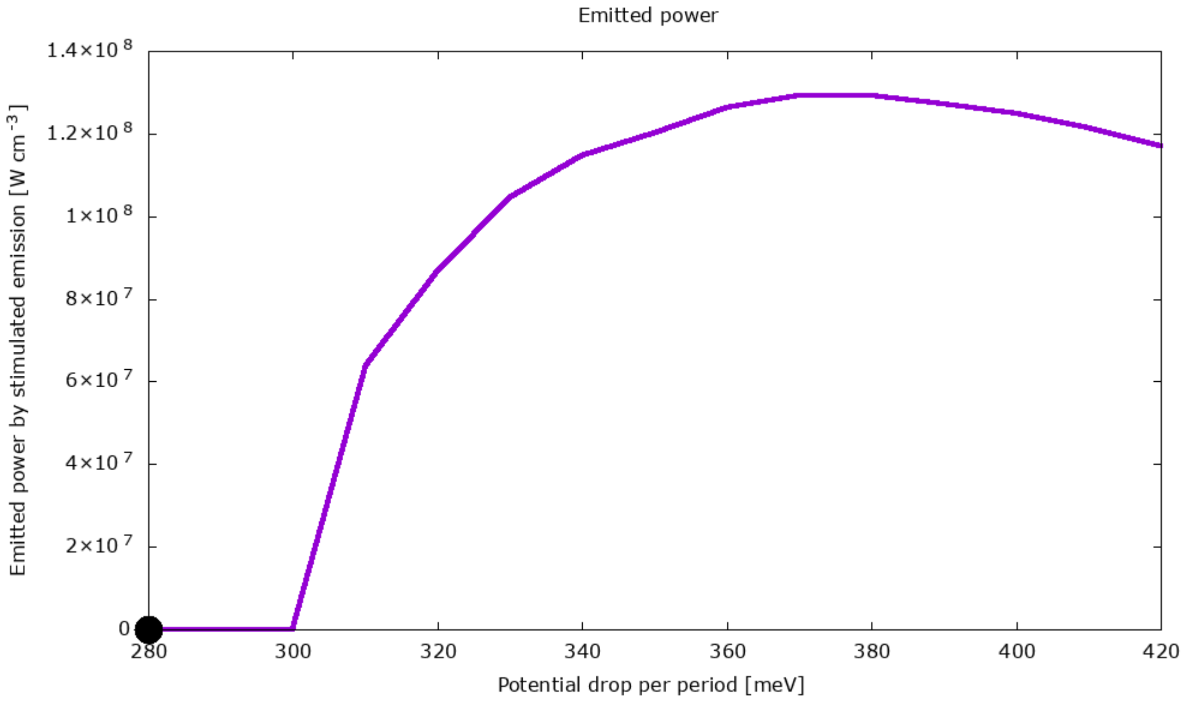
In this case, the electric field in the cavity is adjusted self-consistently so that the gain for this photon energy matchs the specified cavity losses.

Example: Mid-infrared QCL

The following animated gifs show the electron density, current density and output as the voltage is swept. Above the threshold bias (around 300 meV), the clamping of the gain to the cavity losses results a rapid increase in the internal electric field in the cavity. The photon-assisted transport results in a discontinuity in the slope of the current-voltage characteristics at the threshold bias/current: above threshold, the current increases much faster as stimulated emission reduces the upper laser level lifetime.




Current Density
Current Density [A cm^{-2}]
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
280
300
320
340
360
380
400
420
Potential drop per period [meV]


Emitted power
Emitted power by stimulated emission [W cm^{-3}]
1.4×10^{8}
1.2×10^{8}
1×10^{8}
8×10^{7}
6×10^{7}
4×10^{7}
2×10^{7}
0
280
300
320
340
360
380
400
420
Potential drop per period [meV]