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Spin transport in magnetic tunnel junctions

Version: 2016.0

Downloads & Links

- [PDF](#)
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- [Introduction to QuantumATK](#)
- [Transport calculations with QuantumATK](#)
- [AdaptiveGrid](#)
- [ATK Reference Manual](#)
- [central_region.py](#)
- [mgo_para.py](#)
- [mgo_relax.py](#)
- [tmr.py](#)
- [adaptive_grid.py](#)
- [zoom.py](#)
- [mgo_nonco_dc.py](#)
- [mgo_nonco_dc_analysis.py](#)

Introduction

This tutorial shows you how to simulate and analyze the electronic transport properties of magnetic tunnel junctions (MTJs), commonly studied for spintronic applications. You will consider a Fe|MgO|Fe MTJ, which is a rather complex spin polarized system, initially studied by MacLaren and co-workers ^[1].


You will use QuantumATK to study the collinear and non-collinear spin-dependent transport properties, including electronic transmission, tunnel magnetoresistance, and spin-transfer torque. You will also become acquainted with the AdaptiveGrid method, which is an adaptive alternative to the conventional Monkhorst–Pack type grid for k-point sampling.



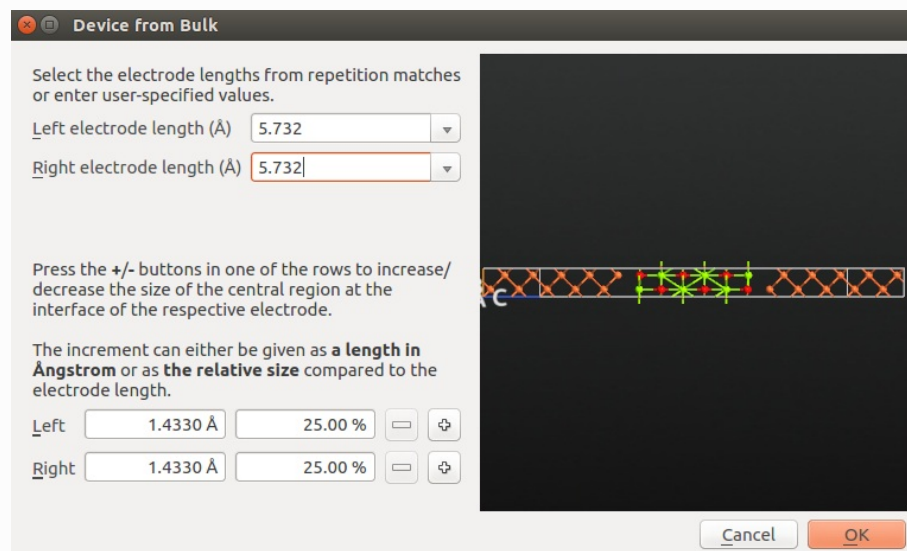
Getting started

It is very easy to create a Fe|MgO|Fe tunnel junction using the *Magnetic Tunnel Junction* Builder plugin. However, the device configuration will then need to be geometry optimized, which is not the main objective of this tutorial. We therefore provide an QuantumATK Python script with the optimized device central region, [central_region.py](#), which you should use for building the MTJ device. You can also jump

to section [Relaxing the device central region](#) if you want to learn how the geometry relaxation was done.

For now, just start QuantumATK, create a new project and give it a name, then select it and click *Open*. Download [central_region.py](#) and save it in the Project Folder. Then drop the script on the QuantumATK  **Builder**, and use the **Device from Bulk** plugin to attach electrodes to the central region, and thereby create the Fe|MgO|Fe device.

The default electrode length of 5.732 Å will work fine for the present purposes. This corresponds to two times the iron lattice constant.






Note

The Device from Bulk plugin will suggest a few different electrode lengths. These are detected by searching for periodicity in your central region. Always check and carefully choose these important parameters. See the tutorial [Transport calculations with QuantumATK](#) for more information.

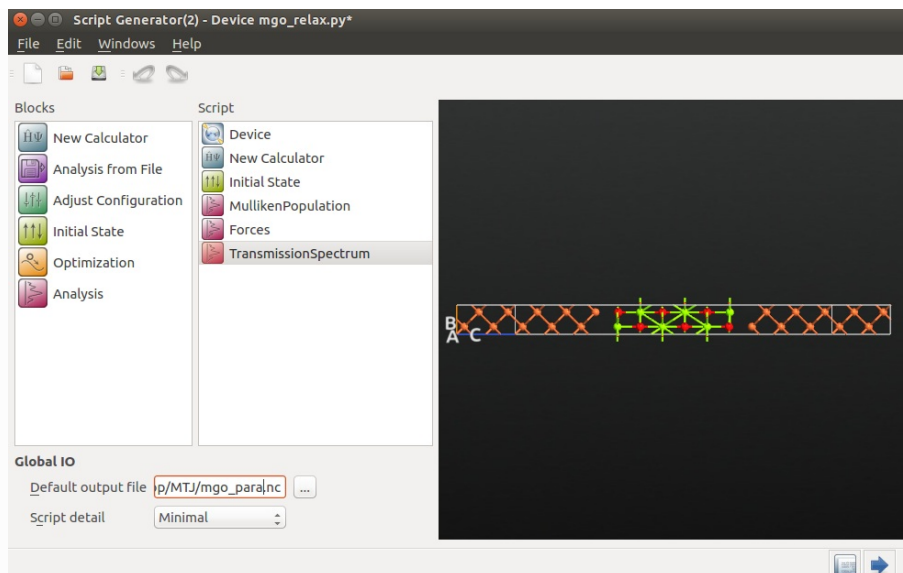
Parallel spin

You will in the following perform a self-consistent NEGF-DFT calculation for the case of parallel spin polarization in the left and right iron parts of the MTJ. You will also compute the transmission spectrum as a function of the k-vector parallel to the transport direction.

Send the device configuration to the  **Script Generator** (use the  icon for this), and add the following blocks to the script:

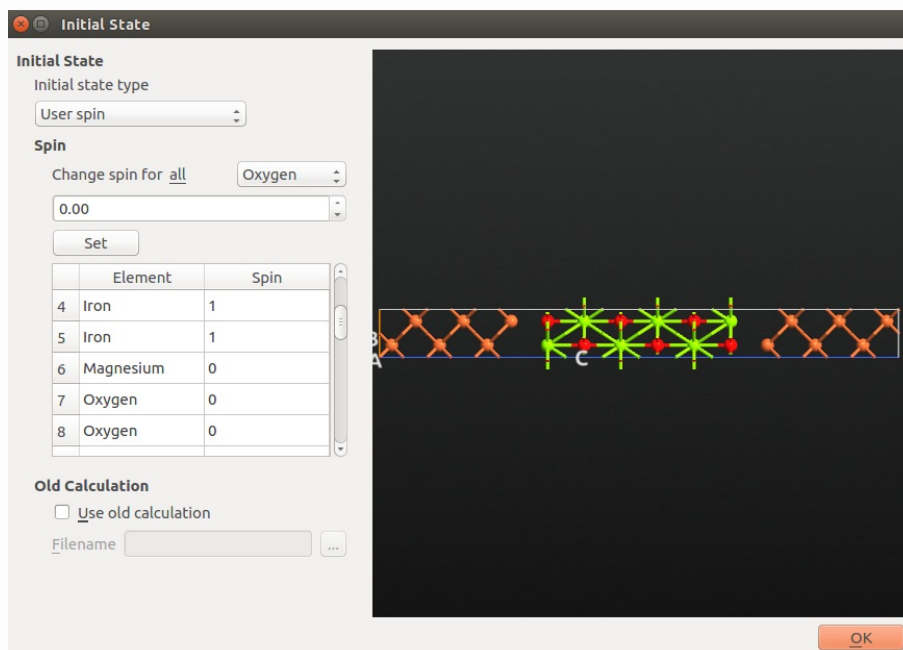
-  New Calculator
-  Initial State
-  MullikenPopulation
-  Forces
-  TransmissionSpectrum

Then change the default output file name to `mgo_para.nc`.

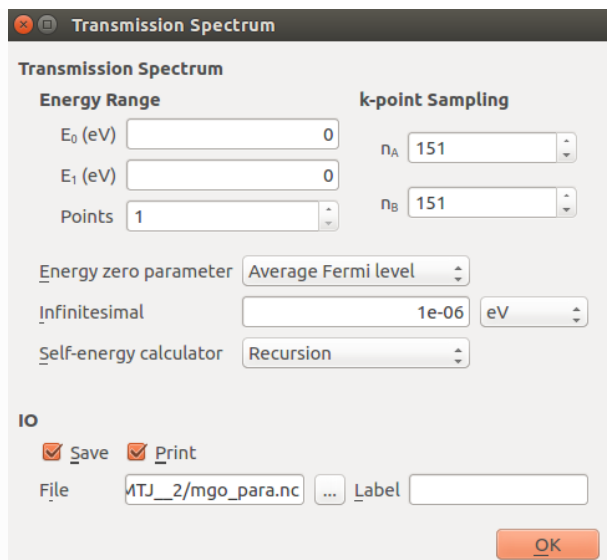


Next, adjust the settings in some of the script blocks:

- **Calculator:**
 - Select the SGGA exchange-correlation method, to perform a spin polarized GGA calculation using the PBE functional.
 - Increase the electron temperature to 1200 Kelvin, to ease the self-consistent convergence.
 - Use a 7x7x100 k-point grid.
 - Select the SingleZetaPolarized basis set for iron.
- **Initial State:**
 - Choose *User spin* for as the type of initial state.
 - Set the relative spins on O and Mg atoms to 0.



- **TransmissionSpectrum:**
 - You will in this example compute the transmission only at the Fermi level, to save time. Use the settings $E_0 = E_1 = 0.0$ eV and just a single energy point to achieve this.
 - 151x151 grid for k-point sampling.



Transmission Spectrum

Energy Range

E₀ (eV)

E₁ (eV)

Points

k-point Sampling

n_A

n_B

Energy zero parameter


Infinitesimal eV

Self-energy calculator

IO

☒ Save ☒ Print

File ... Label

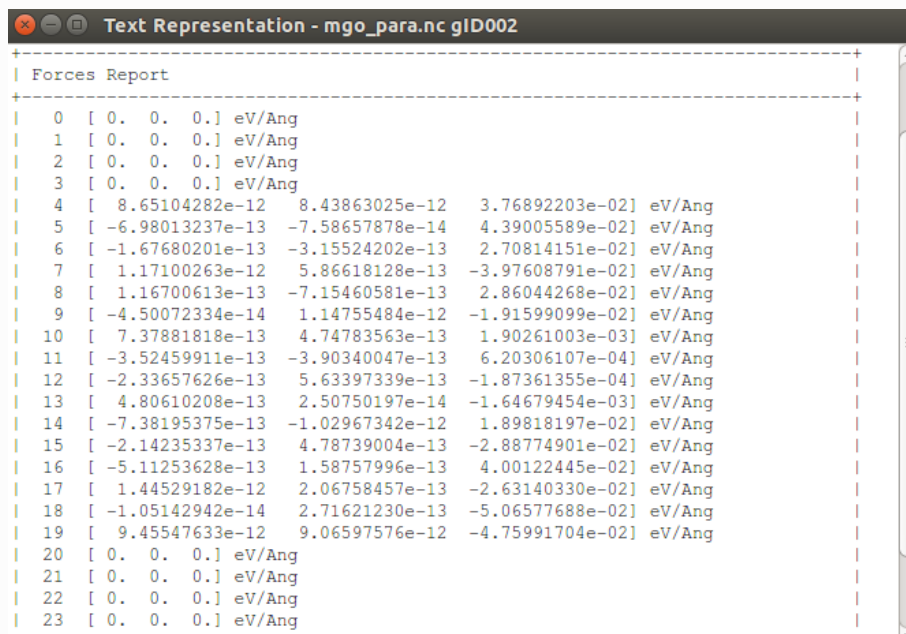
Save the script as `mgo_para.py` and run the calculation, e.g. using the  **Job Manager**. The calculations may take an hour on a single core, but it is possible to obtain a very good speedup by executing in parallel, reducing the computational time down to roughly 20 minutes with 4 MPI processes. If needed you can also download the script: [mgo_para.py](#).

Important

Do not close the Script Generator window. You will need it again later on for setting up calculations for the anti-parallel spin configuration.

Inspecting the forces

The output data file `mgo_para.nc` should now have appeared in the Project Files list. Make sure it is selected, such that the data items are visible on the LabFloor. Then select the **Forces** item and use the **Text Representation** tool in the right-hand Panel Bar to see a report of the forces:



```

Forces Report
+-----+
| 0 | [ 0.  0.  0.] eV/Ang
| 1 | [ 0.  0.  0.] eV/Ang
| 2 | [ 0.  0.  0.] eV/Ang
| 3 | [ 0.  0.  0.] eV/Ang
| 4 | [ 8.65104282e-12  8.43863025e-12  3.76892203e-02] eV/Ang
| 5 | [-6.98013237e-13 -7.58657878e-14  4.39005589e-02] eV/Ang
| 6 | [-1.67680201e-13 -3.15524202e-13  2.70814151e-02] eV/Ang
| 7 | [ 1.17100263e-12  5.86618128e-13 -3.97608791e-02] eV/Ang
| 8 | [ 1.16700613e-13 -7.15460581e-13  2.86044268e-02] eV/Ang
| 9 | [-4.50072334e-14  1.14755484e-12 -1.91599099e-02] eV/Ang
|10 | [ 7.37881818e-13  4.74783563e-13  1.90261003e-03] eV/Ang
|11 | [-3.52459911e-13 -3.90340047e-13  6.20306107e-04] eV/Ang
|12 | [-2.33657626e-13  5.63397339e-13 -1.87361355e-04] eV/Ang
|13 | [ 4.80610208e-13  2.50750197e-14 -1.64679454e-03] eV/Ang
|14 | [-7.38195375e-13 -1.02967342e-12  1.89818197e-02] eV/Ang
|15 | [-2.14235337e-13  4.78739004e-13 -2.88774901e-02] eV/Ang
|16 | [-5.11253628e-13  1.58757996e-13  4.00122445e-02] eV/Ang
|17 | [ 1.44529182e-12  2.06758457e-13 -2.63140330e-02] eV/Ang
|18 | [-1.05142942e-14  2.71621230e-13 -5.06577688e-02] eV/Ang
|19 | [ 9.45547633e-12  9.06597576e-12 -4.75991704e-02] eV/Ang
|20 | [ 0.  0.  0.] eV/Ang
|21 | [ 0.  0.  0.] eV/Ang
|22 | [ 0.  0.  0.] eV/Ang
|23 | [ 0.  0.  0.] eV/Ang

```

The forces on the atoms belonging to the electrode extension regions are not calculated, and these are therefore set to zero. For the other atoms, the forces are small.

Mulliken population

You can also use the Text Representation tool to inspect the calculated **Mulliken populations**:

Text Representation - mgo_para.nc glD001									
3	Fe	5.139	4.372	xy		zy	zz-rr	zx	xx-yy
				0.834		0.837	0.934	0.837	0.929
		2.865	1.979	0.478		0.488	0.257	0.488	0.268
				s					
		0.471	0.500	0.471					
				0.500					
		0.296	0.386	y		z	x		
				0.099		0.097	0.099		
		0.127	0.132	0.127		0.132	0.127		
4	Fe	5.171	4.413	xy		zy	zz-rr	zx	xx-yy
				0.865		0.850	0.929	0.850	0.920
		2.847	1.956	0.489		0.498	0.231	0.498	0.240
				s					
		0.462	0.506	0.462					
				0.506					
		0.297	0.385	y		z	x		
				0.097		0.102	0.097		
		0.127	0.131	0.127		0.131	0.127		
5	Fe	5.529	4.672	xy		zy	zz-rr	zx	xx-yy
				0.914		0.939	0.949	0.939	0.931
		2.478	1.633	0.388		0.349	0.241	0.349	0.306
				s					
		0.487	0.481	0.487					
				0.481					
		0.370	0.364	y		z	x		
				0.135		0.099	0.135		
		0.130	0.104	0.130		0.104	0.130		
6	Mg	0.471	-0.039	s					
				-0.039					
		0.533	-0.048	s					
				-0.048					
		0.201	0.228	s					
				0.228					
		0.310	0.353	y		z	x		
				0.091		0.127	0.091		
		0.092	0.168	0.092		0.168	0.092		
7	O	3.501	0.077	s					
				0.077					
		3.466	0.080	s					
				0.080					
		0.498	0.507	y		z	x		
				0.167		0.165	0.167		

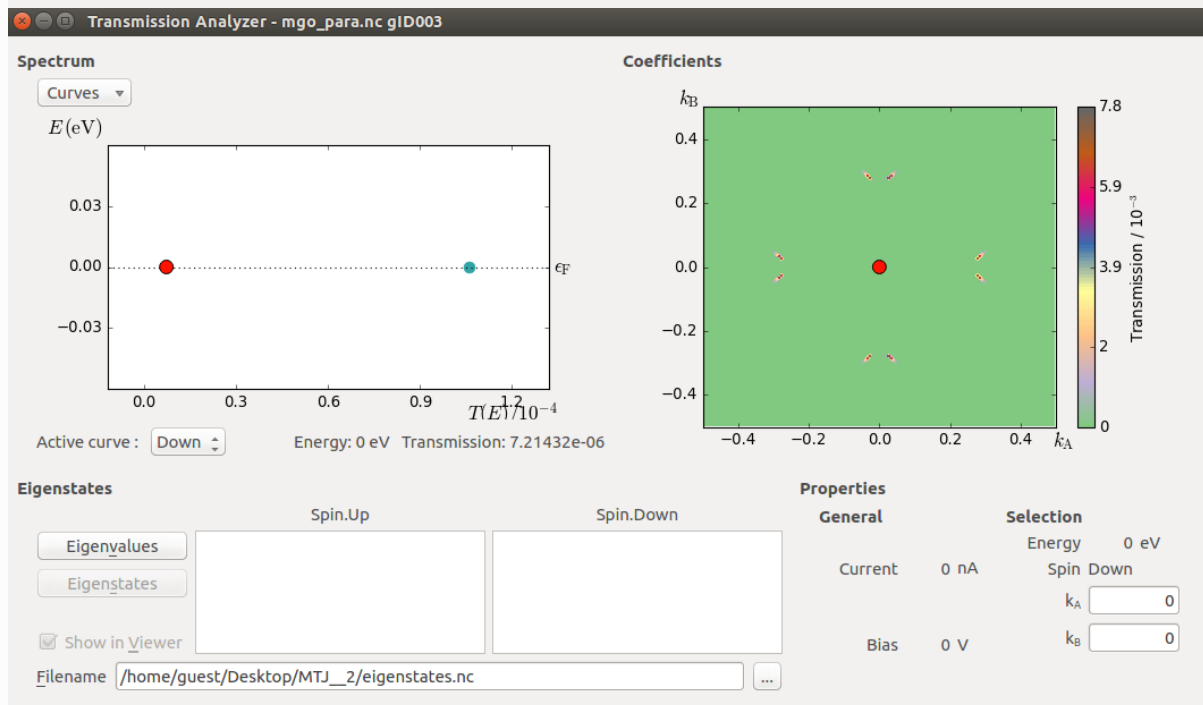
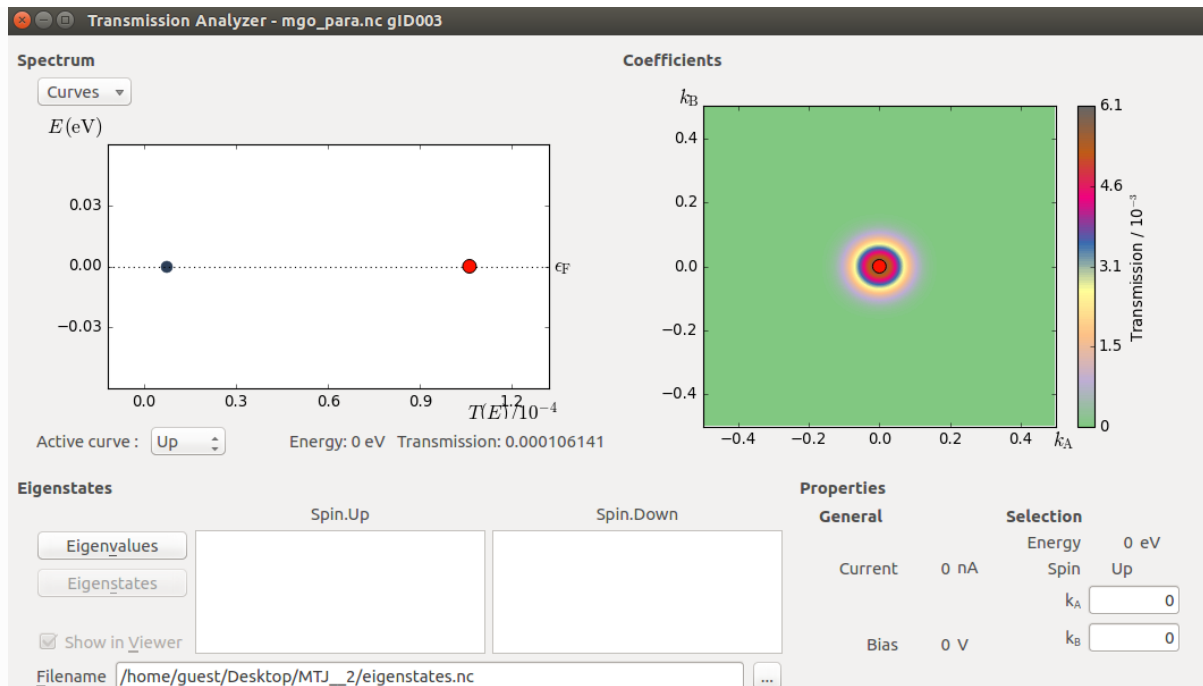
The leftmost column lists the total Mulliken population per spin channel for each atom. It is important to inspect this result in order to check that each atom is correctly spin polarized. Note that all Fe atoms are polarized with their majority spin pointing up, while the O atoms are essentially unpolarized. The Mg atoms next to the interfaces (on both sides) couple anti-parallel with the Fe atoms, while the Mg atoms further away from the interfaces are unpolarized.

The report also shows the population for each shell and resolves it on individual orbitals.

Electron transmission

Use the **Transmission Analyzer** plugin to analyze the calculated transmission spectrum. A few modifications of the plotting options make this spectrum easier to analyze:


- Right-click the right-hand plot of the k-dependent transmission coefficients, and select the color map named *Spectral*.
- In the **Curves** menu, tick off Up and Down.
- Using the **Active Spin** menu, you can now choose between the k-dependent transmission for spin-up and spin-down electrons:

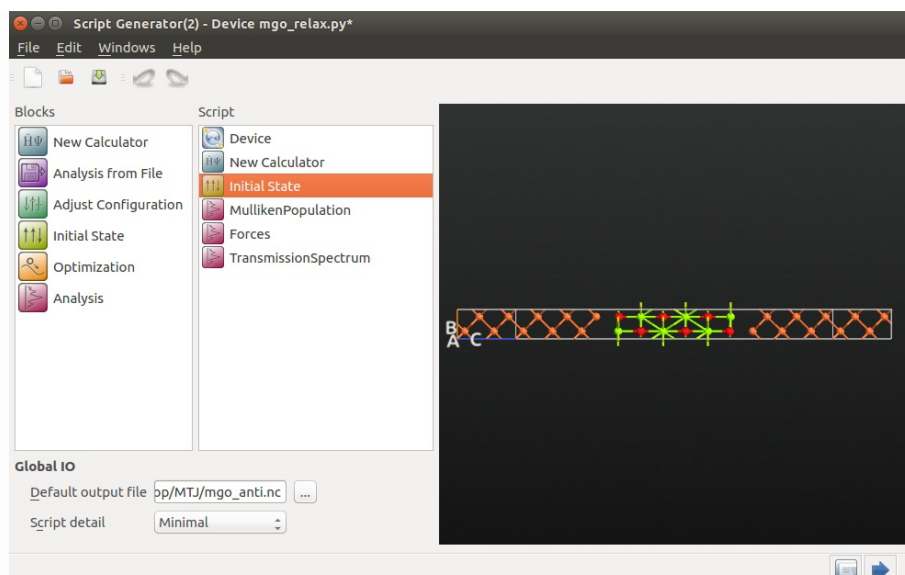


As for the results of the calculation, it is clear from the plots above that the spin-down (minority) transmission is strongly suppressed in magnitude, and exhibits spikes at certain points in the Brillouin zone, corresponding to resonant tunneling, whereas the spin-up (majority) transmission indicates regular barrier tunneling. This is all in agreement with the accepted picture of the tunneling mechanism in the Fe|MgO|Fe tunneling junction (compare to Figures 6 and 10 in [1]).


Anti-parallel spin

We now turn to the case of anti-parallel alignment of the spins in the left and right iron parts of the Fe|MgO|Fe junction. The self-consistent state of the parallel configuration computed above will be used as an initial guess for the anti-parallel state. This speeds up SCF convergence as compared to starting the anti-parallel calculation completely from scratch.

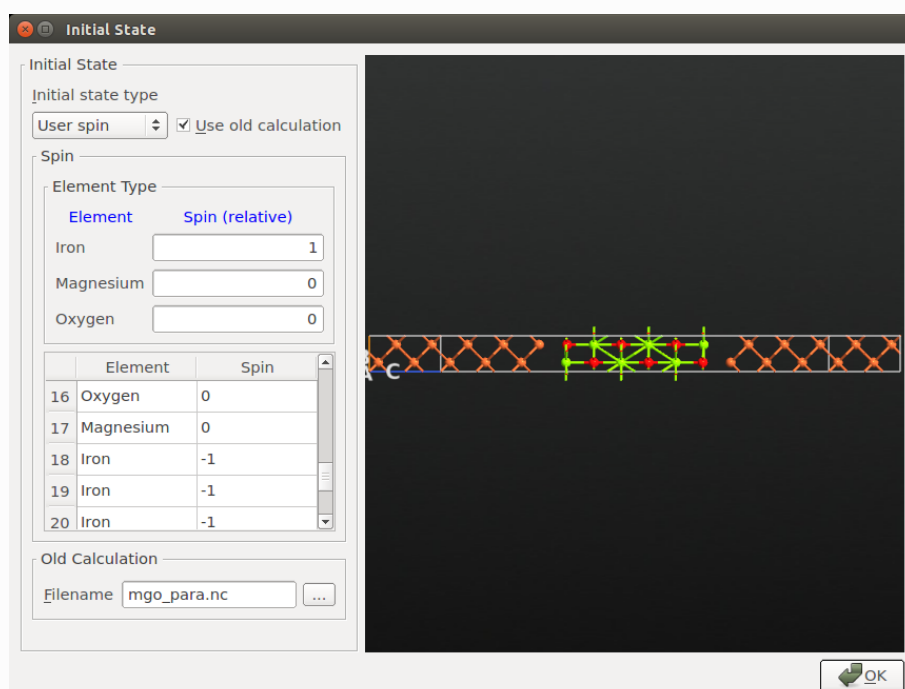
Return to the  **Script Generator**. If you did not close it after setting up the parallel calculation, only a few modifications are needed. Otherwise, drop the script `mgo_para.py` on the Scriptor and start by setting up the script identically to what you did above for the parallel calculations.



Setting the initial state

Open the  **Initial State** block, and do the following to set up the anti-parallel spin configuration and use the parallel calculation as an initial guess for the device density matrix:

- Set again the relative spin for all iron atoms to 1 and set it to 0 for magnesium and oxygen atoms.
- Change the initial spin to -1 for all iron atoms on the right-hand side of the junction.
- Check the *Use old calculation* tick box and enter `mgo_para.nc` as the filename from which the old calculation should be loaded from.



Note

The method outlined above works like this: The converged density matrix from the parallel-spin calculation is used as initial state. However, the spin densities for atoms in the right-hand side of the device are flipped, resulting in an anti-parallel initial density matrix for the full device.

Finally, change the default output file name to `mgo_anti.nc` and make sure the **TransmissionSpectrum**

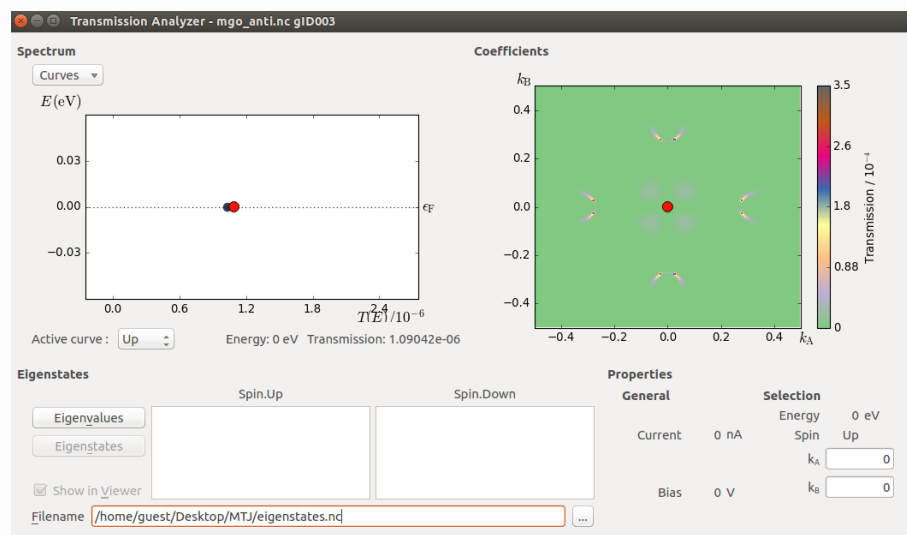
analysis block is identical to the one used for the spin-parallel case.

Save the QuantumATK Python script as `mgo_anti.py` and run it.

Analyzing the results

Check that the forces on each atom are still negligible. Also check the Mulliken populations to ensure that each atom has the expected spin polarization.

Use again the **Transmission Analyzer** to analyze the electronic transmission. In this case, the transmission for up and down (majority and minority) spins are identical because of the mirror symmetry of the system. We find again that the k-dependent transmission coefficients exhibit highly localized peaks surrounded by regions of zero transmission.



To understand why the transmission is identical for spin-up and -down, first note that due to time inversion symmetry, propagation from left to right is always identical to propagation from right to left. The “up” component of the transmission spectrum corresponds to “up” electrons from the left electrode propagation into the right electrode. The “down” component of the transmission spectrum corresponds to “down” electrons in the right electrode propagating into the left electrode.

Due to the anti-symmetric spin, the up electrons in the left electrode and the down electrons in the right electrode are both majority channels. Because of the mirror symmetry of the device, the propagation of the left majority channels into the right minority channels (the first transmission coefficient spin component) and the propagation of the right majority channels into the left minority channels (the second transmission coefficient spin component) are the same.

Thus, for symmetric devices, the equivalence of the two spin channels is an important check for anti-symmetric calculations at zero bias.

Tunneling magnetoresistance

The tunneling magnetoresistance (TMR) is defined as

$$\text{TMR} = \frac{G_P - G_{AP}}{G_{AP}},$$

where

G_P is the conductance through the junction with parallel spin alignment and G_{AP} the conductance for anti-parallel spin alignment.

The conductances can be calculated from their respective transmission spectra. The script below performs this calculation. You can download it here: [tmr.py](#).

```

# Calculate conductance for parallel spin
transmission_para = nload('mgo_para.hdf5', TransmissionSpectrum)[0]
conductance_para_uu = transmission_para.conductance(spin=Spin.Up)
conductance_para_dd = transmission_para.conductance(spin=Spin.Down)
conductance_para = conductance_para_uu + conductance_para_dd

# Calculate conductance for anti-parallel spin
transmission_anti = nload('mgo_anti.hdf5', TransmissionSpectrum)[0]
conductance_anti_uu = transmission_anti.conductance(spin=Spin.Up)
conductance_anti_dd = transmission_anti.conductance(spin=Spin.Down)
conductance_anti = conductance_anti_uu + conductance_anti_dd

print('Conductance Parallel Spin (Siemens)')
print('Up=%8.2e, Down=%8.2e' % (conductance_para_uu.inUnitsOf(Siemens),
                                conductance_para_dd.inUnitsOf(Siemens)))
print('Total = %8.2e' % (conductance_para.inUnitsOf(Siemens)))
print()

print('Conductance Anti-Parallel Spin (Siemens)')
print('Up=%8.2e, Down=%8.2e' % (conductance_anti_uu.inUnitsOf(Siemens),
                                conductance_anti_dd.inUnitsOf(Siemens)))
print('Total = %8.2e' % (conductance_anti.inUnitsOf(Siemens)))
print()

print('TMR (optimistic) = %8.2f percent' % \
      (100.*(conductance_para-conductance_anti)/conductance_anti))
print('TMR (pessimistic) = %8.2f percent' % \
      (100.*(conductance_para-conductance_anti)/(conductance_para+conductance_anti)))

```

Execute the script, and find the TMR:

```

Conductance Parallel Spin (Siemens)
Up=4.11e-09, Down=2.79e-10
Total = 4.39e-09

Conductance Anti-Parallel Spin (Siemens)
Up=4.22e-11, Down=4.00e-11
Total = 8.22e-11

TMR (optimistic) = 5240.12 percent
TMR (pessimistic) = 96.32 percent

```

Adaptive k-point grid

The **AdaptiveGrid** class implements an alternative to the traditional Monkhorst–Pack (MP) grid for k-point sampling. As described in great detail in the QuantumATK Reference Manual entry for [AdaptiveGrid](#), an adaptive k-point grid can be used to automatically zoom in on the significant features of the electron transmission spectrum. This is particularly useful when the k-dependent transmission is dominated by localized peaks, like for the Fe|MgO|Fe MTJ, where the total computed transmission may depend critically on resolving those peaks.

The adaptive algorithm essentially divides the Brillouin zone (BZ) into triangles and integrates over each triangle. Each triangle becomes increasingly small in an iterative manner until convergence is reached, but stops if the number of refinement levels reach the `maximum_number_of_levels`, which is 20 by default. Two types of error measures are available:

Absolute:

Converged when the *absolute* value of the BZ integral in all triangles is lower than the chosen tolerance.

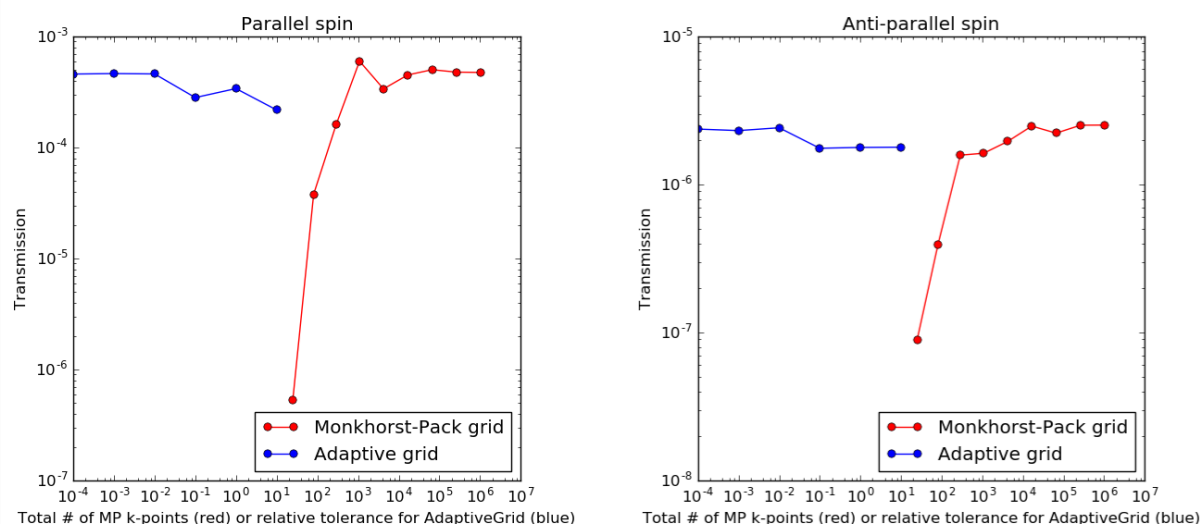
Relative:

Converged when the *relative* value of the BZ integral in all triangles is lower than the chosen **tolerance**.

Note

The AdaptiveGrid functionality is available from QuantumATK 2016 and onwards.

The figures below show how the total transmission through the Fe|MgO|Fe MTJ depends on the k-point resolution used for sampling the k-dependent transmission function for the parallel and anti-parallel cases. Results using the MP k-point grid are compared to those from using the adaptive k-point grid.



Well converged calculations of the total transmission through the MTJ considered here are obtained with no less than 10^3 Monkhorst-Pack k-points, roughly corresponding to a 31×31 grid. With the adaptive k-point grid, a **relative tolerance** of 10^{-2} seems to be quite sufficient.

Note

The computational load for producing the data shown in the figures above increase from right to left with AdaptiveGrid (blue curves), and from left to right with MonkhorstPack (red curves).

Parallel transmission

The script [adaptive_grid.py](#) calculates the transmission for the Fe|MgO|Fe device with parallel spin orientation using both a dense MP grid and the AdaptiveGrid method:

```

# -----
# Load device configuration
# -----
device_configuration = nload('mgo_para.nc', DeviceConfiguration)[0]

# -----
# Transmission Spectrum using a dense Monkhorst-Pack grid.
# -----
transmission_spectrum = TransmissionSpectrum(
    configuration=device_configuration,
    energies=numpy.linspace(0,0,1)*eV,
    kpoints=MonkhorstPackGrid(500,500),
)
nlsave('adaptive_grid.nc', transmission_spectrum)

# -----
# AdaptiveGrid.
# -----
adaptive_grid = AdaptiveGrid(
    tolerance=0.01,
    error_measure=Relative)

# -----
# Transmission Spectrum using the AdaptiveGrid.
# -----
transmission_spectrum = TransmissionSpectrum(
    configuration=device_configuration,
    energies=numpy.linspace(0,0,1)*eV,
    kpoints=adaptive_grid,
)
nlsave('adaptive_grid.nc', transmission_spectrum)

```

The Monkhorst–Pack grid has 500x500 k-points, while the adaptive grid is set up with a relative tolerance of 10^{-2} . Download and run the script. It should finish in roughly 25 minutes if executed in parallel with 4 MPI processes on a modern laptop.

Spin-up transmission

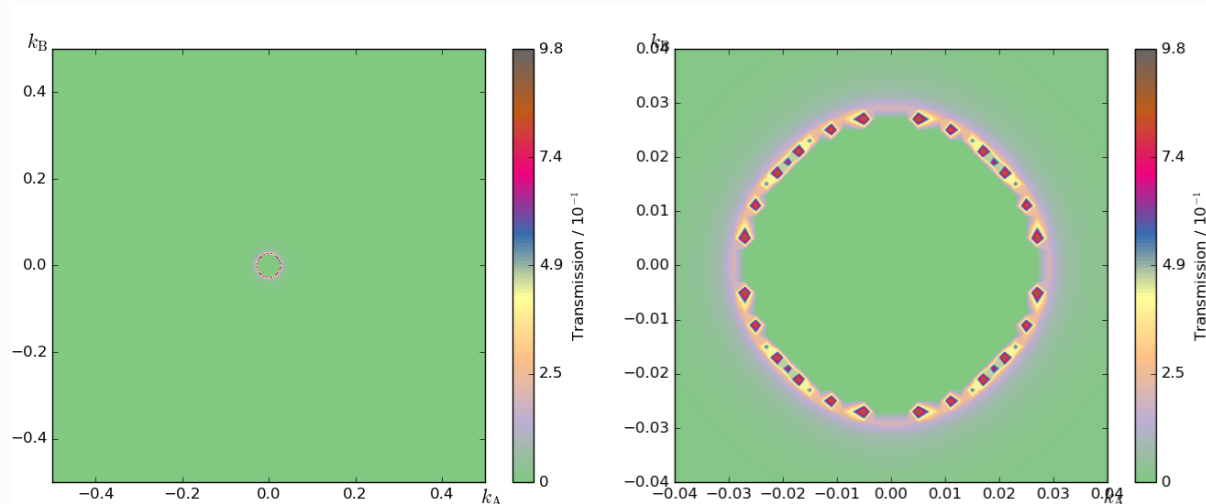



Fig. 87 Spin-up transmission spectrum evaluated using a 500x500 Monkhorst–Pack grid. The total k-point averaged spin-up transmission is $4.6 \cdot 10^{-4}$. Left: Full BZ view. Right: Zoom-in around the Γ point. 

The spin-up spectrum obtained with the dense Monkhorst–Pack grid is different from the one obtained in section [Electron transmission](#) using a less dense grid: We now see that the feature in the middle of the spectrum is actually circular, with zero transmission immediately around the Γ point. Clearly, a very dense grid is needed to resolve this fact. Note, however, that the improved k-point sampling has only increased

the total k-point averaged spin-up transmission by a factor of 4.

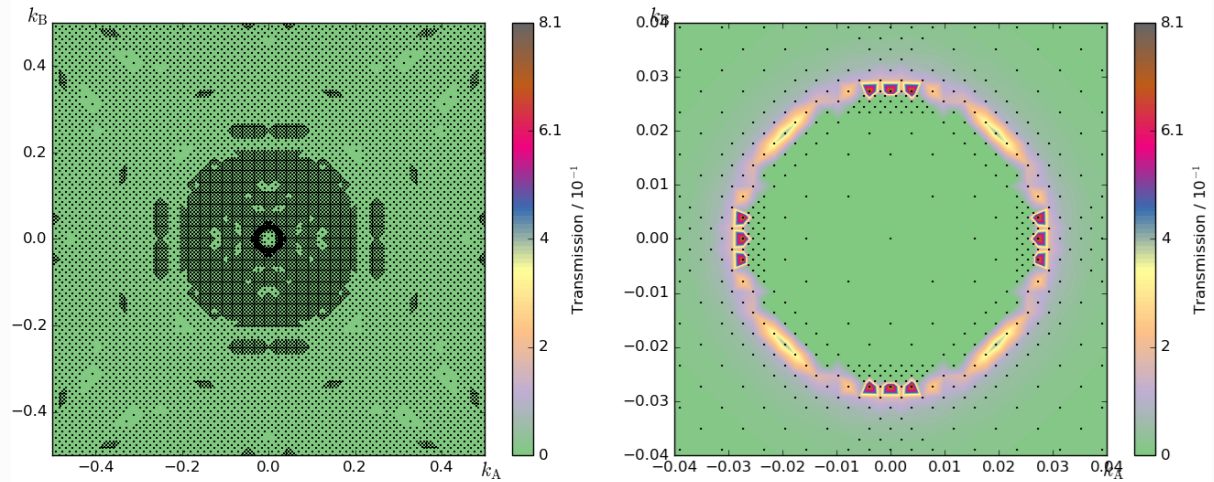



Fig. 88 Spin-up transmission spectrum evaluated using an adaptive grid using a relative tolerance of 10^{-2} . The black dots indicate the sampled k-points. The total k-point averaged spin-up transmission is $4.2 \cdot 10^{-4}$. Left: Full BZ view. Right: Zoom-in around the Γ point. 

The spin-up transmission spectrum evaluated using an adaptive grid is shown in the figure above, where the black dots indicate the sampled k-points. The adaptive algorithm has clearly zoomed in on the circular feature of the k-dependent transmission, causing the k-point density to be largest around the circular transmission feature.

Spin-down transmission

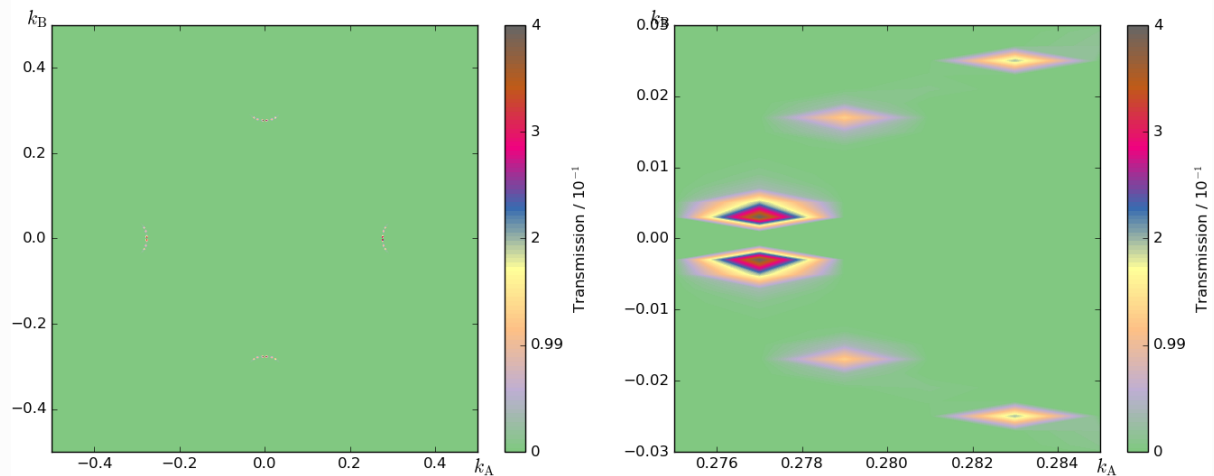



Fig. 89 Spin-down transmission spectrum evaluated using a 500x500 Monkhorst–Pack grid. The total k-point averaged spin-down transmission is $3.7 \cdot 10^{-5}$. Left: Full BZ view. Right: Zoom-in around the right-hand transmission peak. 

The 4 peaks in the densely sampled spin-down transmission are hardly visible before zooming in on one of them. Comparing the transmission obtained using the MP grid (above) to that obtained using the adaptive grid (below), it is again clear that the adaptive algorithm has zoomed in on the transmission peaks. However, the total k-point averaged spin-down transmission has changed only 5%.

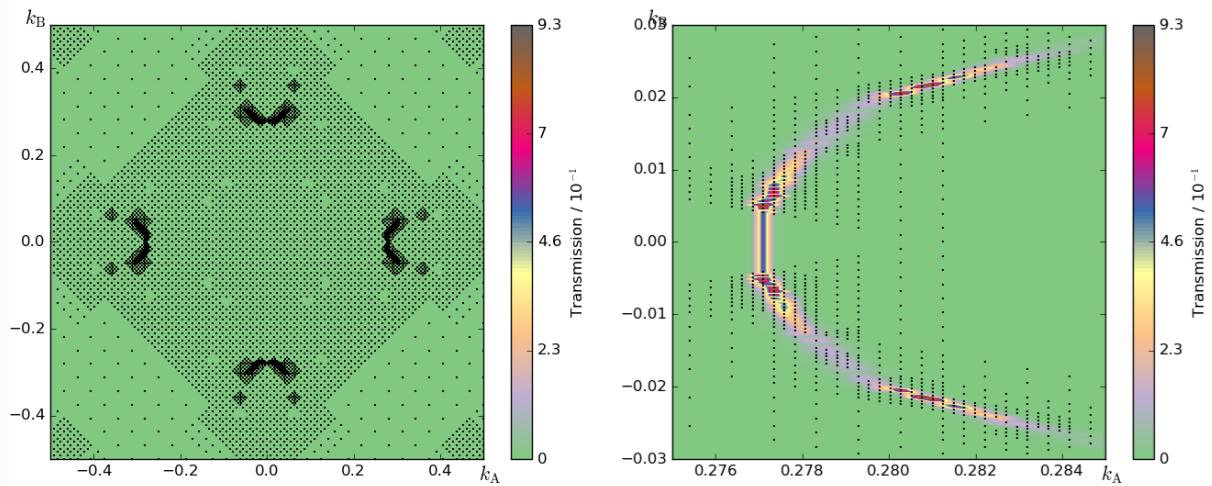


Fig. 90 Spin-down transmission spectrum evaluated using an adaptive grid using a relative tolerance of 10^{-2} . The black dots indicate the sampled k-points. The total k-point averaged spin-down transmission is $3.5 \cdot 10^{-5}$. Left: Full BZ view. Right: Zoom-in around the right-hand transmission peak. 🔍

Restricting the grid range

The AdaptiveGrid class can also be used to resolve only a specific part of the k-dependent transmission. The script shown below ([📄 zoom.py](#)) gives an example of this, where the adaptive grid is restricted to specific

k_A, k_B ranges, and thereby zooms in on specific features of the spin-up and spin-down k-dependent transmissions, respectively. A relative tolerance of 10^{-3} is used to fully resolve the transmission features.

The resulting spin-up and spin-down transmissions are illustrated below. Note the different scales on the figure axes.

```

# -----
# Load device configuration
# -----
device_configuration = nload('mgo_para.nc', DeviceConfiguration)[0]

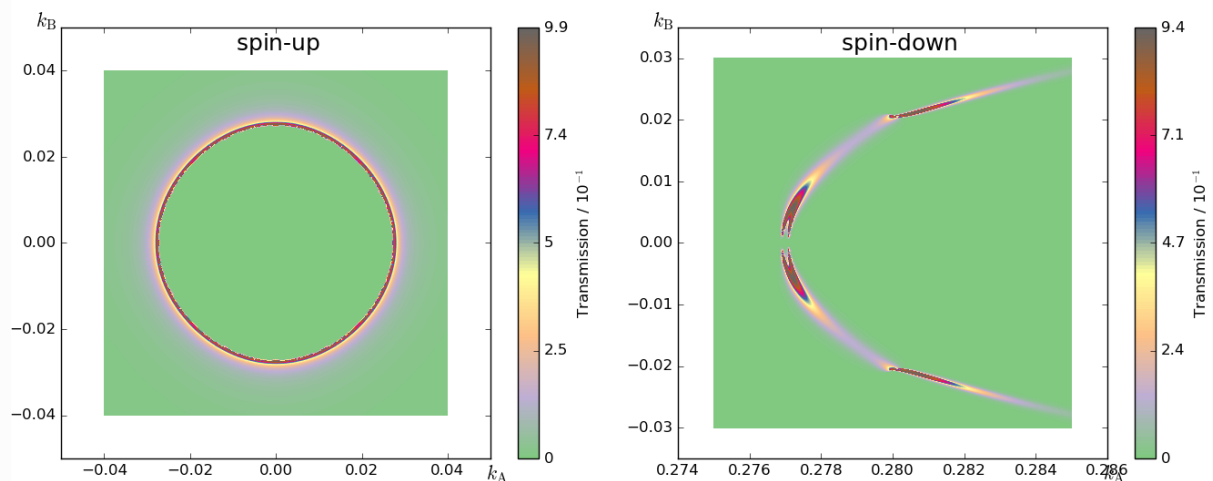
# -----
# Transmission Spectrum zoom #1.
# -----
adaptive_grid = AdaptiveGrid(
    kA_range=[-0.04, 0.04],
    kB_range=[-0.04, 0.04],
    tolerance=0.001,
    error_measure=Relative)

transmission_spectrum = TransmissionSpectrum(
    configuration=device_configuration,
    energies=numpy.linspace(0,0,1)*eV,
    kpoints=adaptive_grid,
)
nlsave('zoom.nc', transmission_spectrum)

# -----
# Transmission Spectrum zoom #2.
# -----
adaptive_grid = AdaptiveGrid(
    kA_range=[0.275, 0.285],
    kB_range=[-0.03, 0.03],
    tolerance=0.001,
    error_measure=Relative)

transmission_spectrum = TransmissionSpectrum(
    configuration=device_configuration,
    energies=numpy.linspace(0,0,1)*eV,
    kpoints=adaptive_grid,
)
nlsave('zoom.nc', transmission_spectrum)

```



Warning

The total (k-point averaged) transmission is most likely not correct if you choose to sample only a specific part of the Brillouin zone. Use full-zone sampling to compute the total transmission through the device, which is also the default setting.

Spin-transfer torque

You will in this section compute the spin transfer torque (STT), which requires non-collinear spin. The tutorial [Introduction to noncollinear spin](#) gives for more information on how to perform STT calculations and non-collinear spin.

In the following, you will:

1. calculate the non-collinear device configuration;
2. calculate the Mulliken population and spin transfer torque.

Computing the non-collinear device configuration

The script [mgo_nonco_dc.py](#) calculates the non-collinear ground state of the device configuration by using the collinear ferromagnetic calculation as starting point and a density mixing scheme which diagonalizes the density matrix before mixing it. Please, note that this script replaces the spin polarized exchange-correlation (SGGA.PBE) by the non-collinear one (NCGGA.PBE).

```
# Read in the collinear calculation
device_configuration = nload('mgo_para.nc', DeviceConfiguration)[0]

# Use the special noncollinear mixing scheme
iteration_control_parameters = IterationControlParameters(
    algorithm=PulayMixer(noncollinear_mixing=True)
)

# Get the calculator
calculator = device_configuration.calculator()
new_calculator = calculator(
    exchange_correlation=NCGGA.PBE,
    iteration_control_parameters = iteration_control_parameters
)


# Define the spin rotation
theta = 120*Degrees
left_spins = [(i, 1, 0*Degrees, 0*Degrees) for i in range(3)]
center_spins = [(i+3, 1, theta*i/5, 0*Degrees) for i in range(6)]
right_spins = [(i+9, 1, theta, 0*Degrees) for i in range(3)]
spin_list = left_spins+center_spins+right_spins
initial_spin = InitialSpin(scaled_spins=spin_list)



# Setup the initial state
device_configuration.setCalculator(
    calculator=new_calculator,
    initial_spin=initial_spin,
    initial_state=device_configuration)


# Calculate and save
device_configuration.update()
nlsave("mgo_nonco_dc.nc", device_configuration)
```

The spin setup corresponds to the spin polarization of the atoms in the left electrode pointing along the transport axis Z, while in the right electrode the polarization is rotated 120 degrees. In the central region, the angle is interpolated between these two values. Note that this is just the initial spin configuration – the actual spin polarization vectors will be computed selfconsistently and may therefore change (you can see the results in the next section).

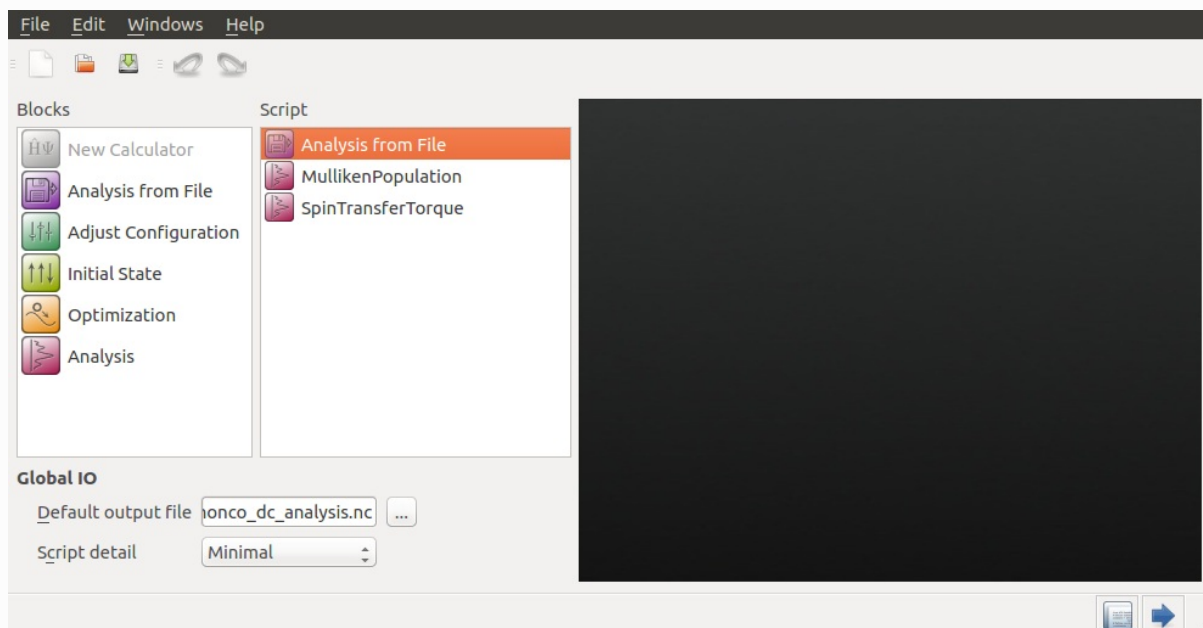
Calculate the Mulliken population and spin transfer torque

Once the calculation is finished you can find the non-collinear device configuration in the LabFloor. In order to calculate the Mulliken population and spin transfer torque, go to the  **Script Generator** and add the following blocks to the script:

-  Analysis from File
-  MullikenPopulation

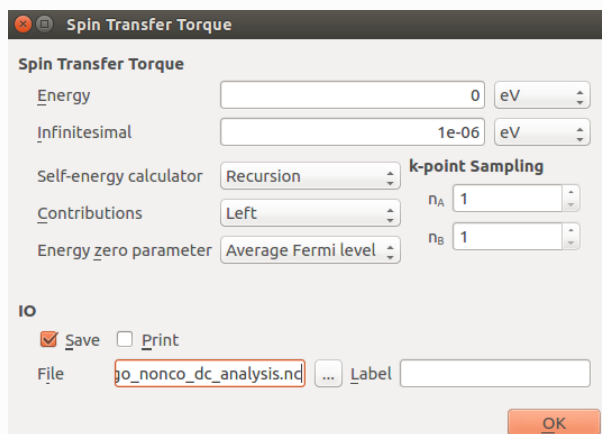
-  SpinTransferTorque


Then, change the default output file name to `mgo_nonco_dc_analysis.nc`.



Adjust the settings in some of the blocks:

- **Analysis From File:**
 - select the `mgo_nonco_dc.nc` file.
- **SpinTransferTorque:**
 - Select **Left** for the contributions. This way, you will calculate the **left** → **right** linear response current.



Send the script to the editor using the send to button (the  icon) and replace the Monkhorst-Pack grid with the Adaptive grid as shown below.

```

# Setup adaptive grid object.
adaptive_grid = AdaptiveGrid(
    kA_range=[-0.5, 0.5],
    kB_range=[-0.5, 0.5],
    tolerance=1e-2,
    error_measure=Relative,
)

# -----
# Spin Transfer Torque
# -----

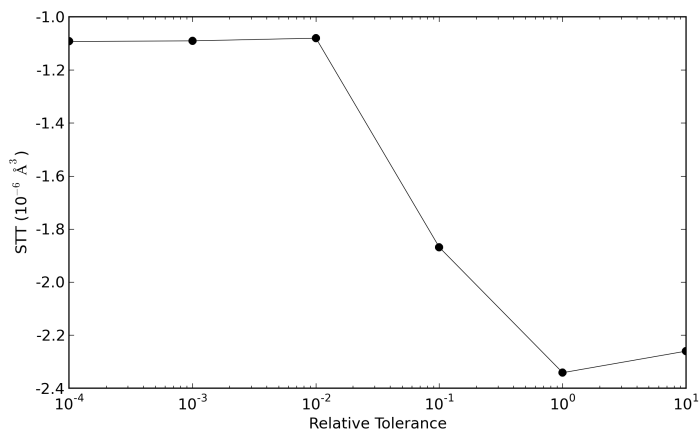
spin_transfer_torque = SpinTransferTorque(
    configuration=device_configuration,
    energy=0*eV,
    kpoints=adaptive_grid,
    contributions=Left,
    energy_zero_parameter=AverageFermiLevel,
    infinitesimal=1e-06*eV,
    self_energy_calculator=RecursionSelfEnergy(),
)

nlsave('mgo_nonco_dc_analysis.nc', spin_transfer_torque)

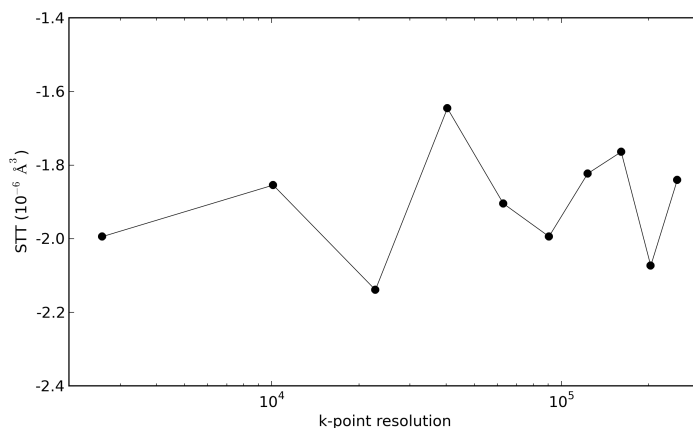
```

If you wish, you can download the script here ([📄 mgo_nonco_dc_analysis.py](#)).

The STT should be computed using a k-point sampling that is dense enough to get a well-converged value for the total torque on the right-hand side of the device. In this script we are using the adaptive grid with a relative tolerance of 10^{-2} . The below figure shows the total spin transfer torque transferred at the right side through Fe|MgO|Fe MTJ for different relative tolerances.



This plot shows that the use of a relative tolerance of 10^{-2} seems to be sufficient to obtain converged calculations of the MTJ considered in this tutorial. We have also computed the total spintransfertorque at the right side using a increasingly denser Monkhorst-Pack grid.




It can be seen that using a Monkhorst-Pack grid the total STT does not reach full convergece.

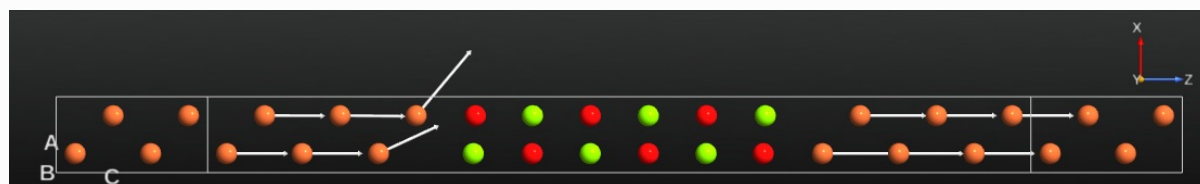
Analysis of the results

Once the calculation is finished, you will get the **MullikenPopulation** and **SpinTransferTorque** objects in the LabFloor. You can inspect the Mulliken charge and the component of the spin polarization vector using the text representation.

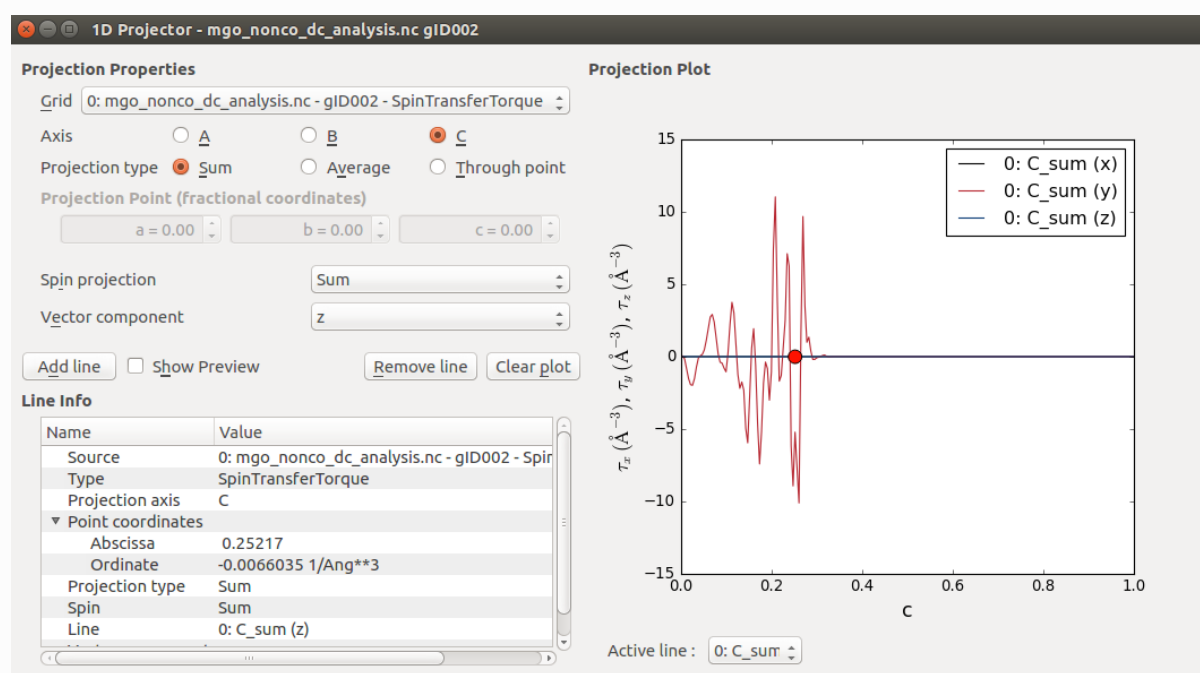
Text Representation - mgo_nonco_dc_analysis.nc gID001

	Element	Up	Down	Theta (Degrees)	Phi (Degrees)
0	Fe	5.0867	2.9217	0.0677	359.7676
1	Fe	5.0633	2.9370	0.1560	180.1813
2	Fe	5.0576	2.9400	0.0348	358.7518
3	Fe	5.1583	2.8468	0.5838	180.1091
4	Fe	5.1849	2.8335	24.8154	0.0034
5	Fe	5.5418	2.4686	49.8978	359.9971
6	Mg	0.5278	0.4751	135.7503	180.0182
7	O	3.4988	3.4673	65.4680	0.0035
8	O	3.5211	3.5194	59.5990	0.0220
9	Mg	0.4820	0.4752	37.2865	359.6952
10	Mg	0.4789	0.4786	52.7842	1.2203
11	O	3.5218	3.5216	30.5324	0.2408
12	O	3.5218	3.5216	2.1668	0.0697
13	Mg	0.4788	0.4787	11.8829	358.7890
14	Mg	0.4819	0.4753	0.0557	0.7770
15	O	3.5210	3.5195	0.0599	359.8667
16	O	3.5008	3.4657	0.0004	359.9098
17	Mg	0.5326	0.4722	179.9986	0.1708
18	Fe	5.5300	2.4769	0.0000	179.5913
19	Fe	5.1796	2.8391	0.0000	359.9876
20	Fe	5.1499	2.8555	0.0000	180.0096
21	Fe	5.0520	2.9460	0.0000	0.0127
22	Fe	5.0695	2.9308	0.0000	359.6984
23	Fe	5.0823	2.9116	0.0000	0.0180

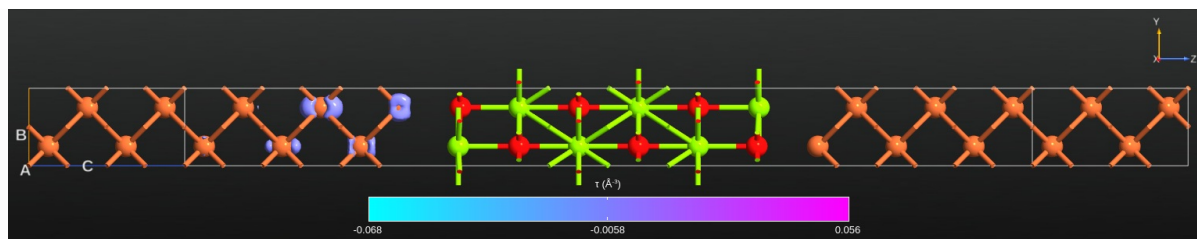
In the noncolinear calculations, the sum of the 'up' and 'down' populations corresponds to the usual Mulliken charge (the number of electrons), and their difference – combined with the two angles – forms the spin polarization vector. This vector can be visualized using the  **Viewer**:



You can also plot the spatial components of the STT using the **1D Projector**:



The figure below shows the MTJ configuration and the "y" component of the STT.



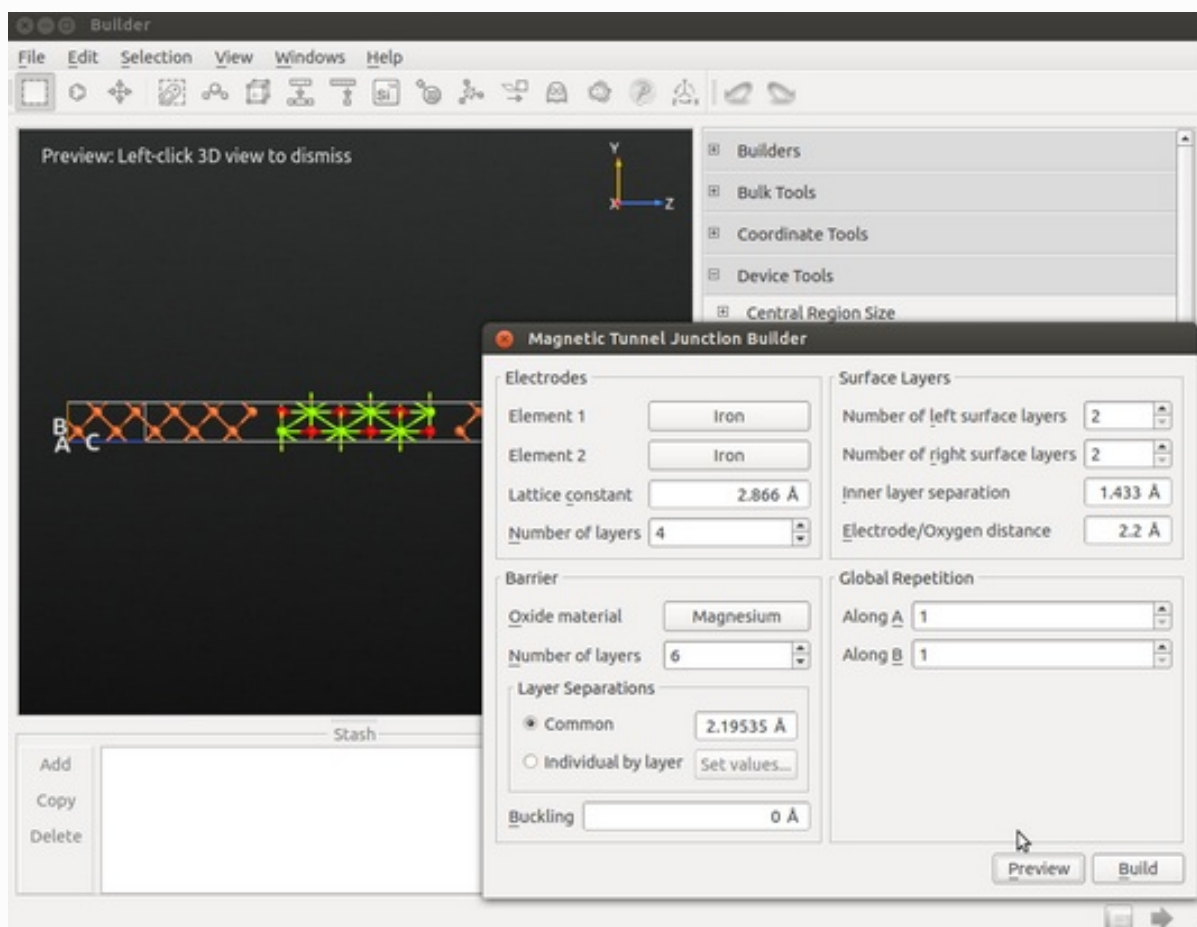
Relaxing the device central region

This section shows you how to create and geometry optimize the central region in the Fe|MgO|Fe junction. The tutorial [Advanced device relaxation - manual workflow](#) gives more detailed instructions for full device optimizations, including relaxed electrodes and optimum central region length. For the sake of simplicity, we here perform force minimization for the device central region only.

Initial configuration


First, open the Builder. To set up the initial geometry of the Fe|MgO|Fe device you will use the **MTJ Builder** plugin, which is designed specifically for constructing this type of geometry. Locate it like this: Add ► From Plugin ► Magnetic Tunnel Junction (FeMgO-style).

The MTJ builder can build a range of different magnetic tunnel junction geometries. For the present purpose, change the number of barrier layers to 6, and the number of surface layers to 2 on both the left and right side, but leave the other parameters as they are by default. Click the **Preview** button to see the geometry, then click **Build** to add it to the Stash.







Tip

Hover the mouse over each input field to get a description of the input parameters.

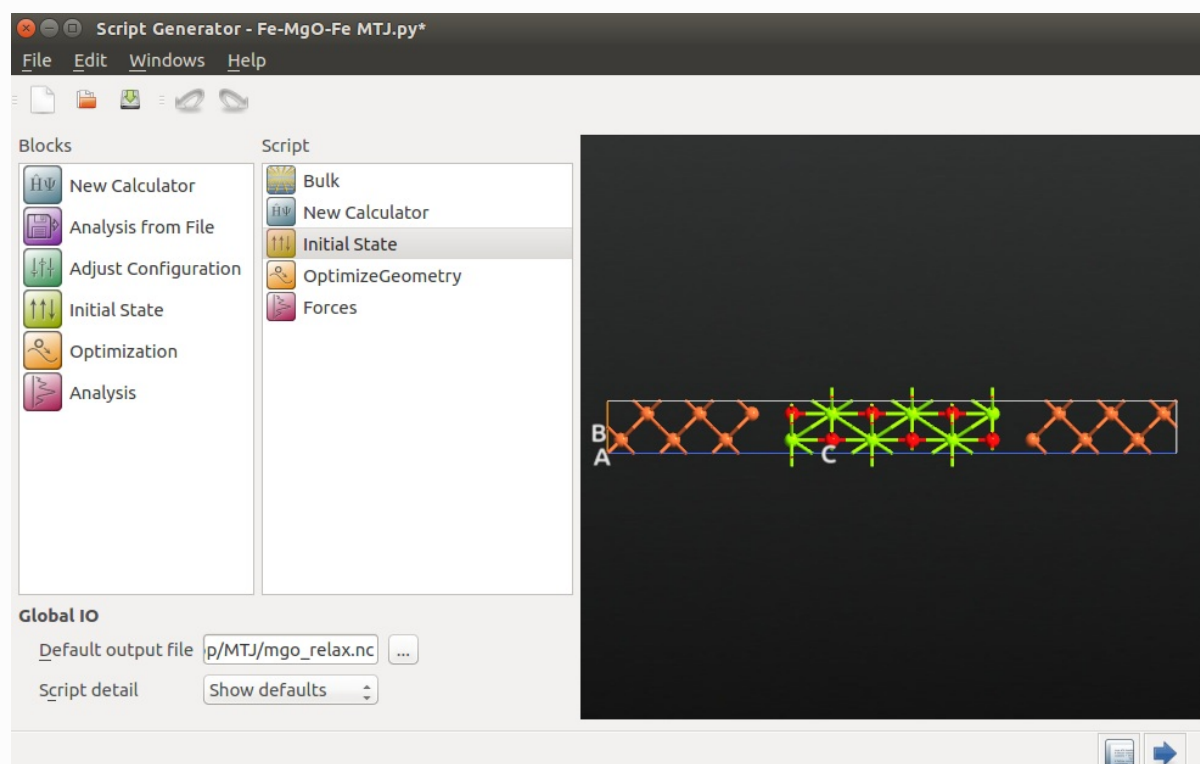
Convert the device geometry to a bulk configuration by clicking the  **Bulk** tool on the plugins toolbar. This simply removes the electrodes and leaves you with the bulk central region.

Geometry optimization

Send the device central region to the  **Script Generator** and add the following blocks to the script:


-  New Calculator
-  Initial State
-  OptimizeGeometry
-  Forces

Also, change the default output filename to `mgo_relax.nc`



The Calculator and InitialState settings should be very similar to those used in section [Parallel spin](#):

- **Calculator:**
 - Select the SGGA exchange-correlation method.
 - Increase the electron temperature to 1200 Kelvin.
 - Set the k-point grid to 7x7x2. This choice gives a reasonable k-point sampling in the x and y directions. In the z direction, you would like to model a device configuration, so the iron atoms at the edges must be bulk-like. Selecting 2 k-points in the z-direction improves the bulk like description of the Fe edge atoms.
 - Select the SingleZetaPolarized basis set for iron.
- **Initial State:**
 - Choose *User spin* for as the type of initial state.
 - Set the relative spins on O and Mg atoms to 0.

Next, open the  **Optimization** block to specify that the first and last four atoms in the central region (the atoms in the electrode extensions) should be kept fixed during the relaxation. This is very important – if

Click *Add Constraints* to open the **Constraints Editor**. Then do the following:

- Select the atoms indicated in the image below by holding down the Ctrl key and drawing a rectangle around them. Then click *Add tag from Selection* to assign the tag “Selection 0” to those atoms. Change the constraint type to “Rigid” for this tag group.
- Do the same for the right-hand electrode extension atoms, but leave the constraint type as “Fixed”.

Optimize Geometry

Optimize Geometry

Force tolerance

0.05

eV/Å

Stress tolerance

0.1

GPa

↑

↓

Maximum number of steps

200

↓

Maximum step size

0.2

Å

Optimizer Method

LBFGS

↑

↓

Target Stress

☒ Isotropic pressure

0

0

0

0

GPa

↑

↓

0

0

0

Lattice Constraints

☒ Constrain Lattice Vectors
 ☒ x
 ☒ y
 ☒ z

☒ Constrain Bravais Lattice: Unit Cell

Atomic Constraint Editor

☐ Save trajectory

...

IO

☒ Save
 ☒ Print

File

p/MTJ/mgo_relax.nc

...

Label

OK

Constraints Editor

For the atom indices associated with a given tag, change the combo box in the **Constraint** column to the desired constraint. To apply constraints to the current selection, press the **Add Selection** button.

Notice that *rigid body* constraints may **not** share atom indices. In this case, table entries are displayed in **red**.

Tag	Constraint
Selection 0	Rigid

Cancel OK

Save the script as `mgo_relax.py` and run it using the Job Manager or from the command line:

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If needed, you can also download the script here: [mgo_relax.py](#). This calculation will take a 1-2 hours on a standard PC, but may finish in 20 minutes if distributed over 4 parallel MPI processes.

Inspecting the results

Locate the calculation data items on the **LabFloor**. Select the **Forces** item (*gID002*), and click the **Text Representation** plugin. You will now see a report of the final forces on all atoms.

```
Text Representation - mgo_relax.nc gID002
# Item: 0
# File: /home/guest/Desktop/MTJ/mgo_relax.nc
# Title: mgo_relax.nc - gID002
# Type: Forces
+-----+
| Forces Report |
+-----+
| 0 | [-5.65166433e-13 -2.98611144e-13 -9.01817935e-02] eV/Ang |
| 1 | [ 6.64493502e-12 6.52651480e-12 2.94255336e-02] eV/Ang |
| 2 | [ 1.36823030e-12 1.95106286e-12 -1.00136659e-01] eV/Ang |
| 3 | [-8.80667107e-12 -8.91005512e-12 -1.28493796e-01] eV/Ang |
| 4 | [ 6.51485018e-12 6.03326508e-12 4.26430559e-02] eV/Ang |
| 5 | [ 2.04540092e-12 1.95944348e-12 4.62198920e-02] eV/Ang |
| 6 | [-2.37574737e-13 1.70103226e-13 2.44565333e-02] eV/Ang |
| 7 | [ 5.65371777e-13 4.78715809e-13 -1.87839167e-02] eV/Ang |
| 8 | [ 6.44396562e-13 3.09377807e-14 4.22671554e-02] eV/Ang |
| 9 | [-3.17920036e-13 1.90817595e-13 -1.78024014e-02] eV/Ang |
| 10 | [ 2.39036696e-13 -1.42687211e-13 6.38323635e-03] eV/Ang |
| 11 | [-9.01442166e-14 3.67834264e-13 5.32441803e-03] eV/Ang |
| 12 | [ 4.81927740e-13 6.67437624e-14 -6.05958779e-03] eV/Ang |
| 13 | [ 8.34988325e-14 1.70593147e-13 -5.67429277e-03] eV/Ang |
| 14 | [-2.10890956e-14 3.37287204e-14 1.85028336e-02] eV/Ang |
| 15 | [ 4.25436429e-13 7.27451603e-14 -4.28807194e-02] eV/Ang |
| 16 | [ 1.86917685e-13 1.50087159e-13 1.85504931e-02] eV/Ang |
| 17 | [ 6.00559901e-13 2.32819142e-13 -2.46488340e-02] eV/Ang |
| 18 | [ 1.37458279e-12 1.99913731e-12 -4.16245073e-02] eV/Ang |
| 19 | [ 4.42454411e-12 5.54030364e-12 -3.40699334e-02] eV/Ang |
| 20 | [-5.65094164e-12 -7.22871690e-12 1.17937925e-01] eV/Ang |
| 21 | [ 8.76830526e-12 1.10265548e-11 9.98868244e-02] eV/Ang |
| 22 | [-1.87565300e-11 -2.07851072e-11 -3.01908210e-02] eV/Ang |
| 23 | [-7.04845969e-14 -2.85051189e-13 9.13089459e-02] eV/Ang |
+-----+
```

Note that all forces in the x-y direction are for all practical purposes zero. For the atoms which have been relaxed, the forces are less than the optimization criterion of 0.05 eV/Ang. For the electrode extension atoms, the forces are slightly larger. Moreover, the force vectors point out of the cell, indicating that the cell is under compressive strain. Adding more surface layers to increase the cell length in the z-direction would lower the strain, but would have very little effect on results in the present case.

You can now use the optimized device central region for calculations of transport properties of the device, c.f. section [Getting started](#).

References

[1] (1,2)

W. H. Butler, X.-G. Zhang, T. C. Schulthess, and J. M. MacLaren. Spin-dependent tunneling conductance of Fe|MgO|Fe sandwiches. *Physical Review B*, 63(5):054416, 2001. doi:10.1103/PhysRevB.63.054416.

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