Lecture 5

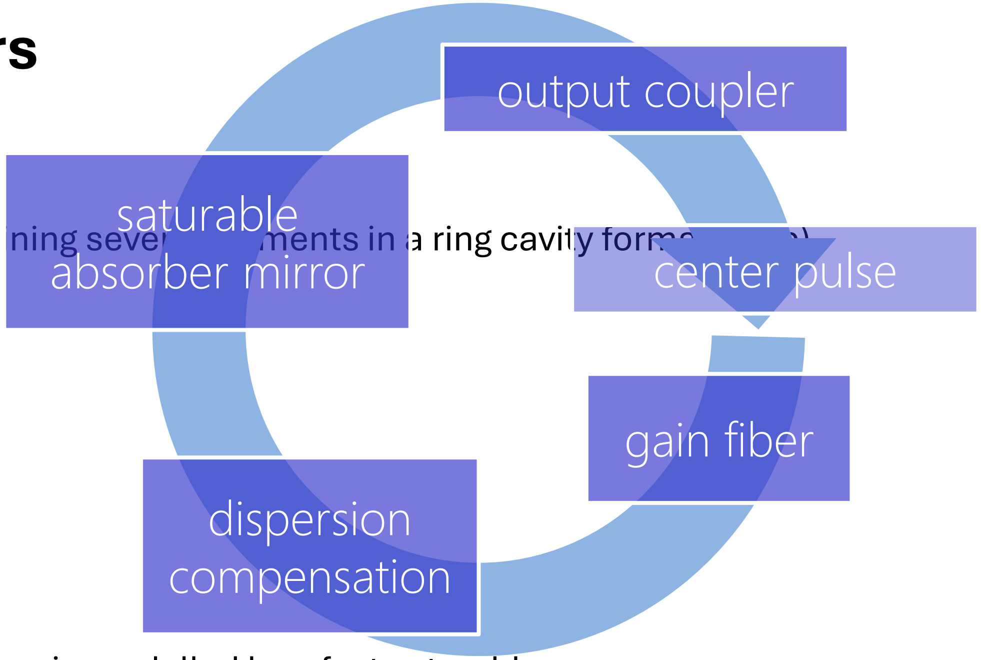
Multi-Element Propagation

Part 1:
Short Pulse Fiber Laser

Part 2:
Mamyshev Oscillator

Part 3:
Micro Comb Generator

Multi-Element Propagation: Short Pulse Fiber Lasers



The layout of a typical short pulse oscillator (not only fiber laser) is shown in the image conta ning sever ments in a ring cavity form

Each Element is modelled by an element typically based on the NLSE:

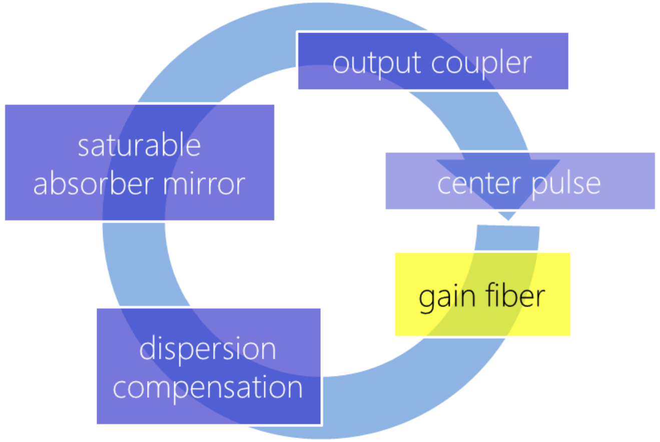
$$iA_z + \frac{g}{2}A + i\beta_2 A_{tt} = i\gamma |A|^2 A$$

Other elements might be simulated by other means, for example, the saturable absorber mirror is modelled by a fast saturable reflectivity/transmission according to:

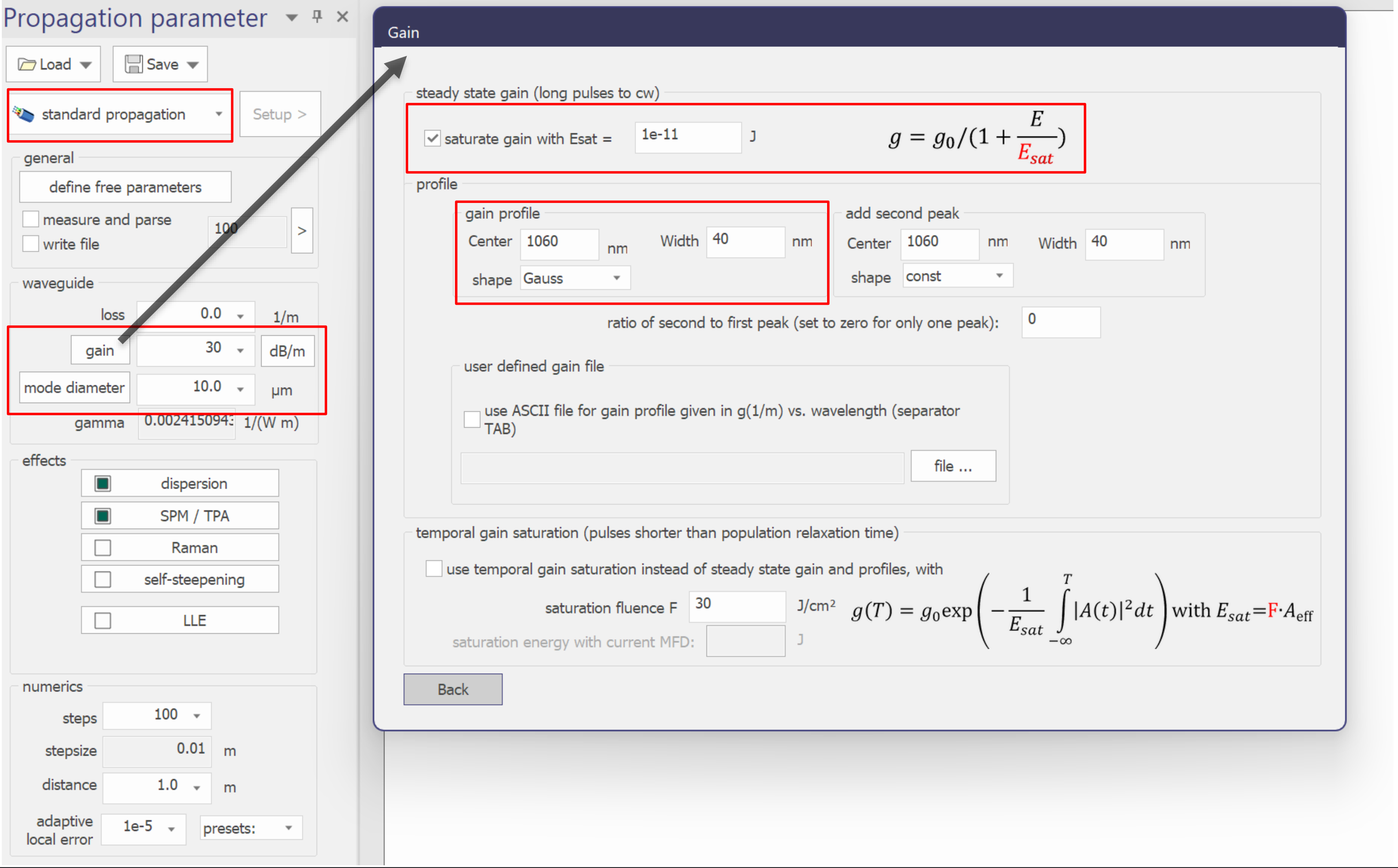
$$R = R_{unsat} + R_{sat} \cdot \left(1 - \frac{1}{1 + P / P_{sat}}\right)$$

Each element setup used for this tutorial example is explained in the following >>

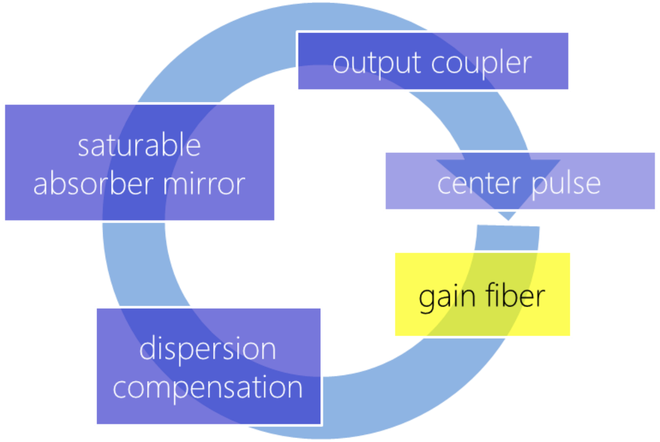
Multi-Element Propagation: Short Pulse Fiber Lasers



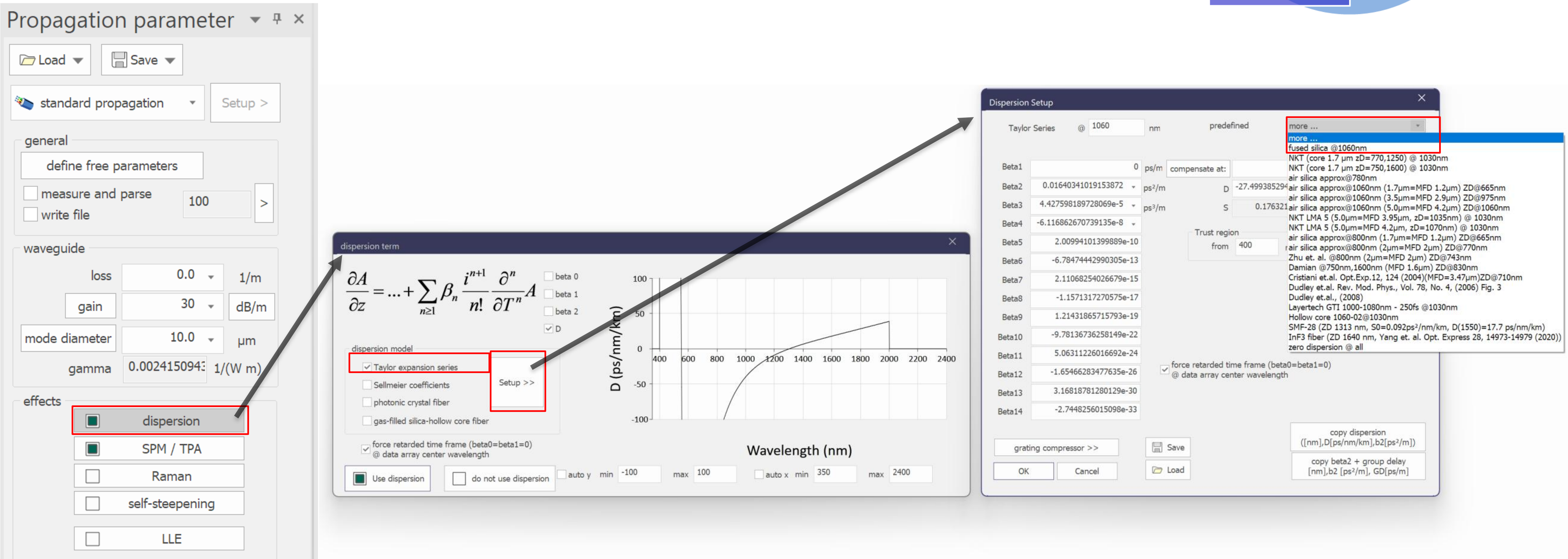
Set up the gain fiber as a *standard propagation* with saturable gain. We also use 10 um mode field diameter and a Gaussian gain spectrum of 40 nm width around 1060 nm.



Multi-Element Propagation: Short Pulse Fiber Lasers



Now set the dispersion of that gain fiber to the dispersion of fused silica (e.g. predefined with its Taylor series at 1060 nm)



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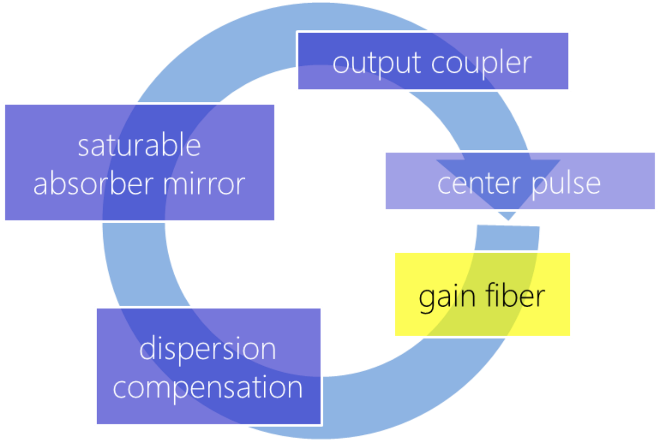
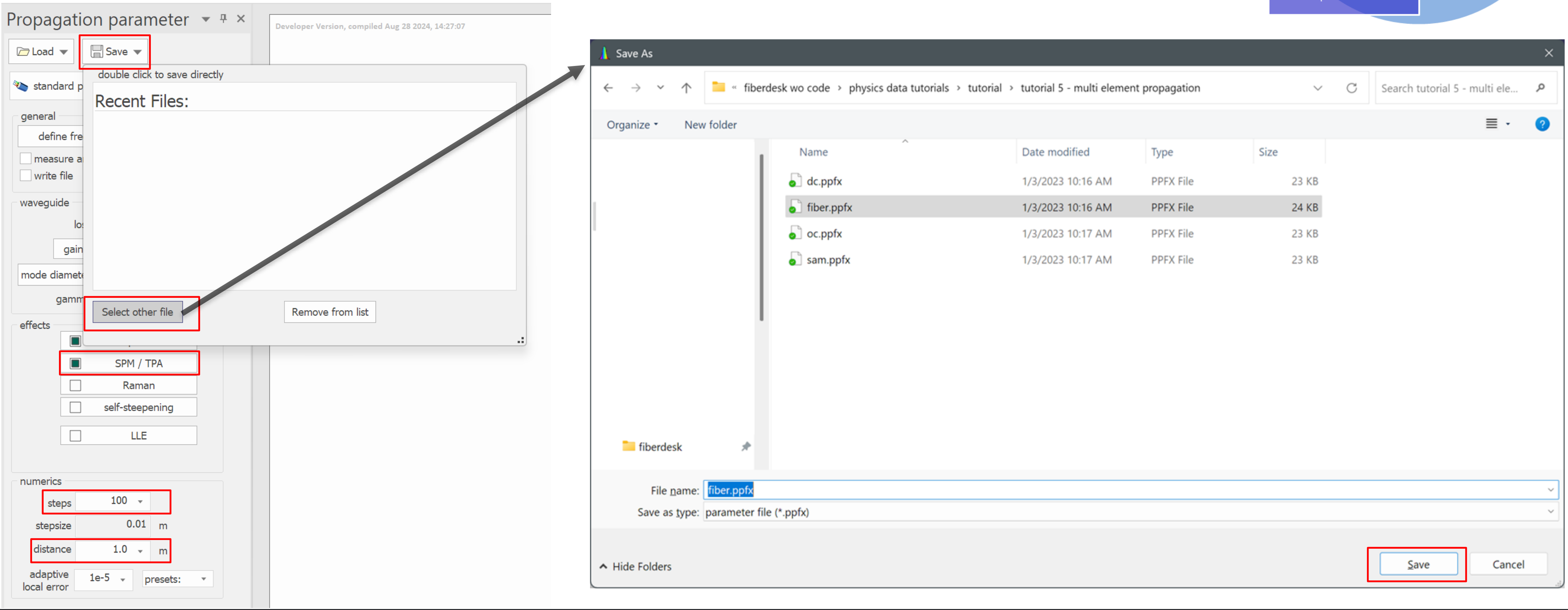
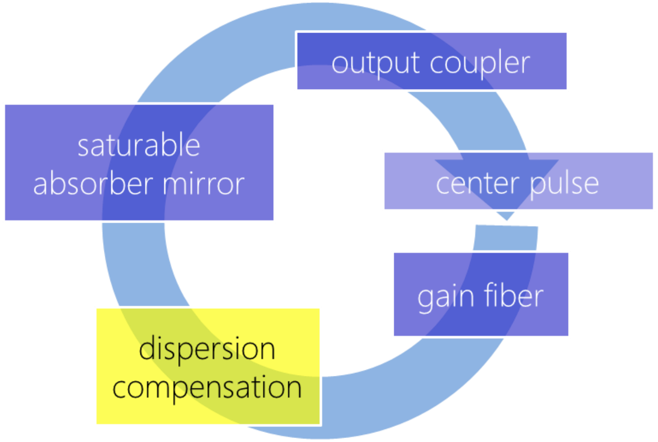


Switch on SPM, set the standard values here and make the propagation 1 m long with 100 steps.

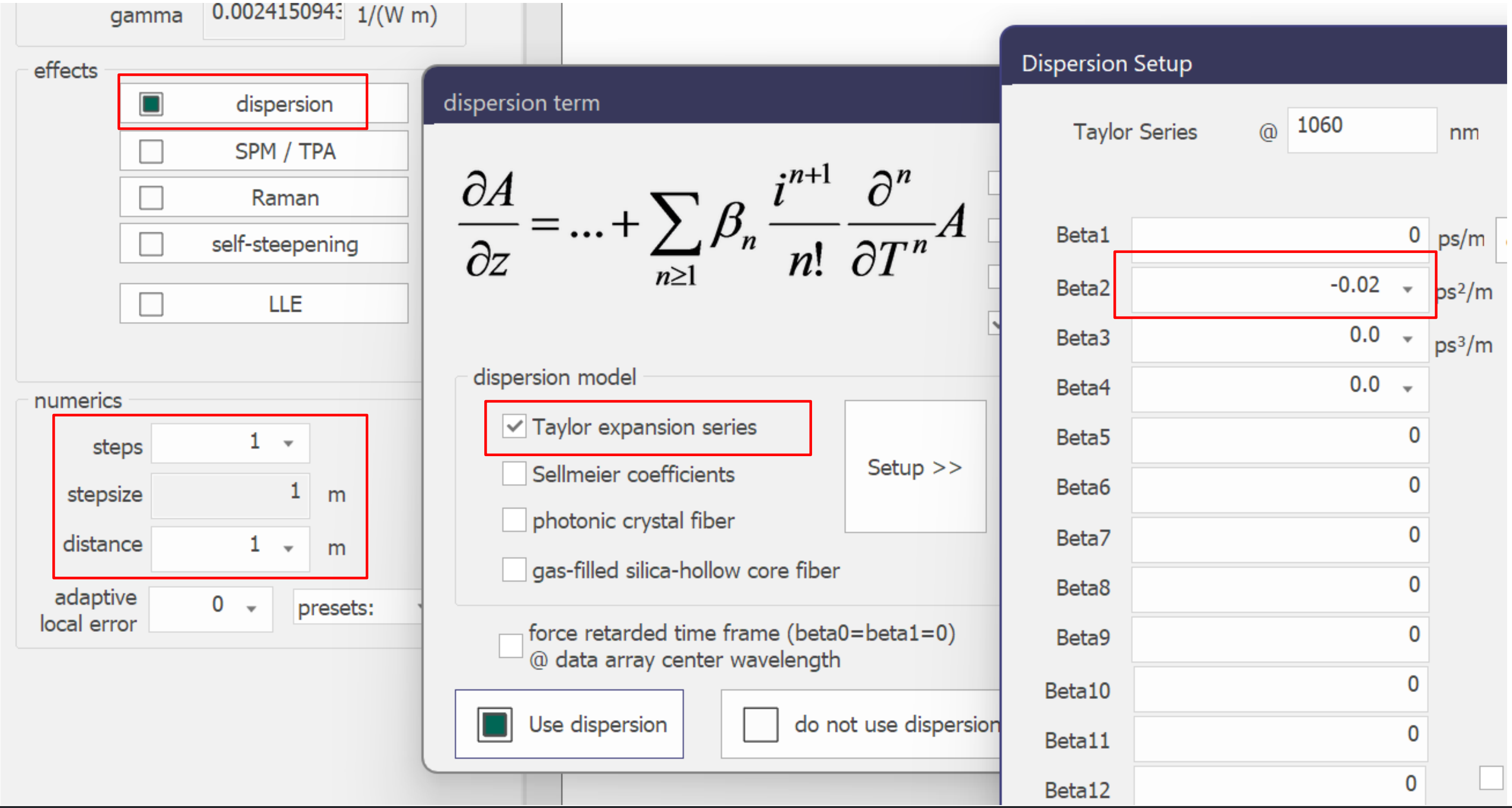
Now save the amplifier to the file „fiber.ppfx“ for later use as an element.



Multi-Element Propagation: Short Pulse Fiber Lasers

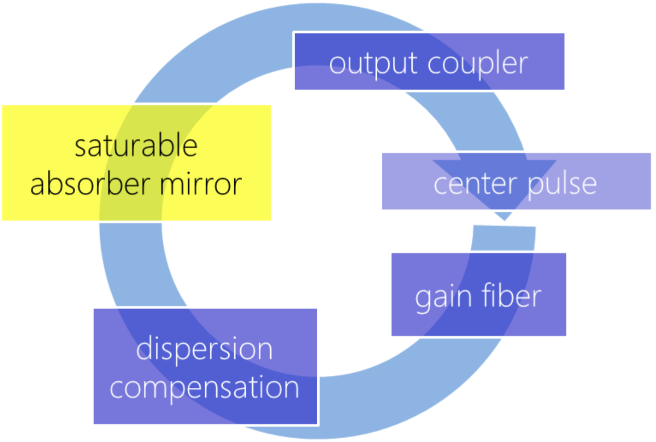


For the dispersion compensation, we only set second order dispersion in the dispersion dialog
Furthermore, set the gain to zero, switch off SPM etc. Only dispersion need to be set.
As it is a linear step, a single step is enough.



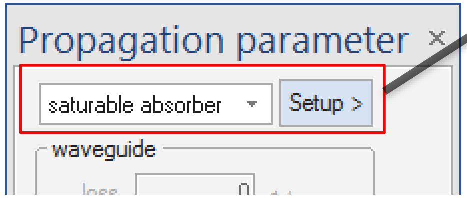
Save the element as dispersion compensation „dc.ppfx“, as done before, for later use as an element.

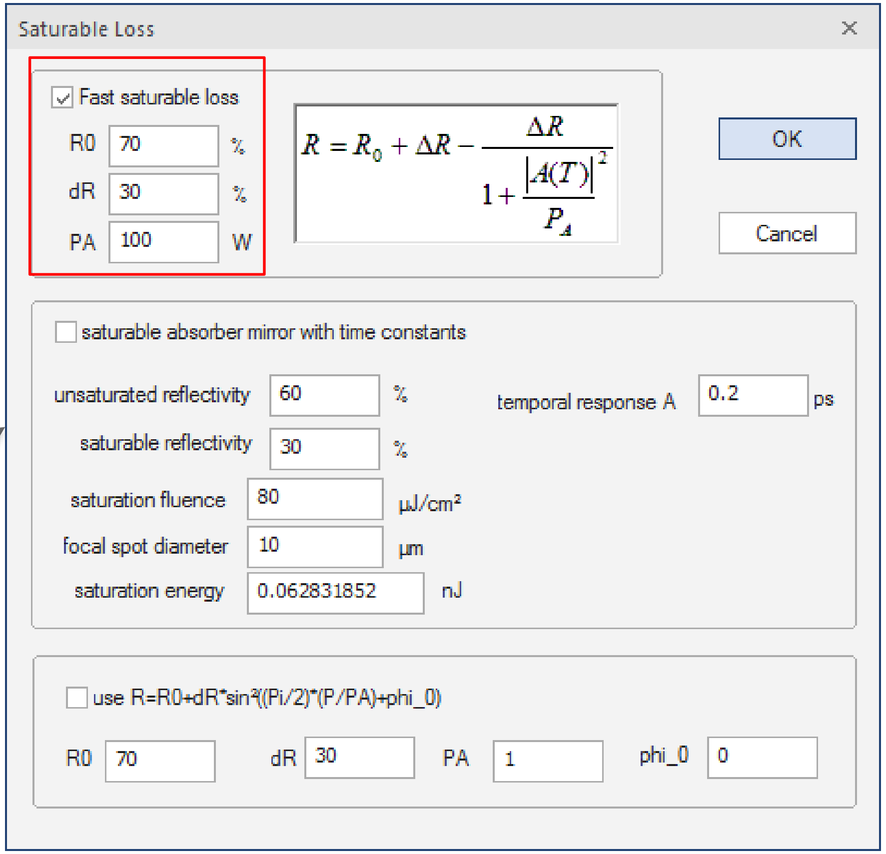
Multi-Element Propagation: Short Pulse Fiber Lasers



The saturable absorber is a different model, select „saturable absorber“ on top of the propagation parameter dialog.

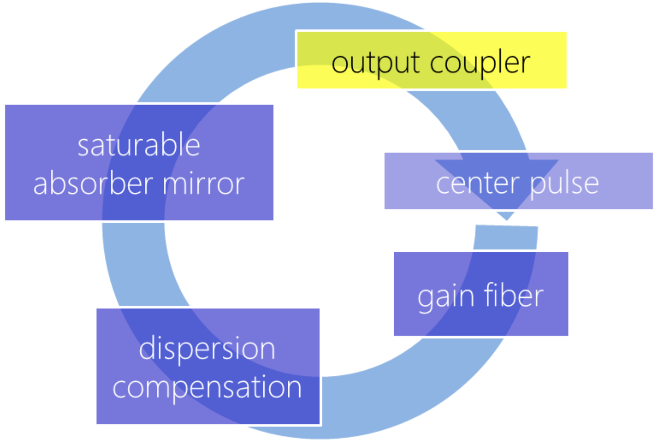
Then, set it up with the parameters on the right.



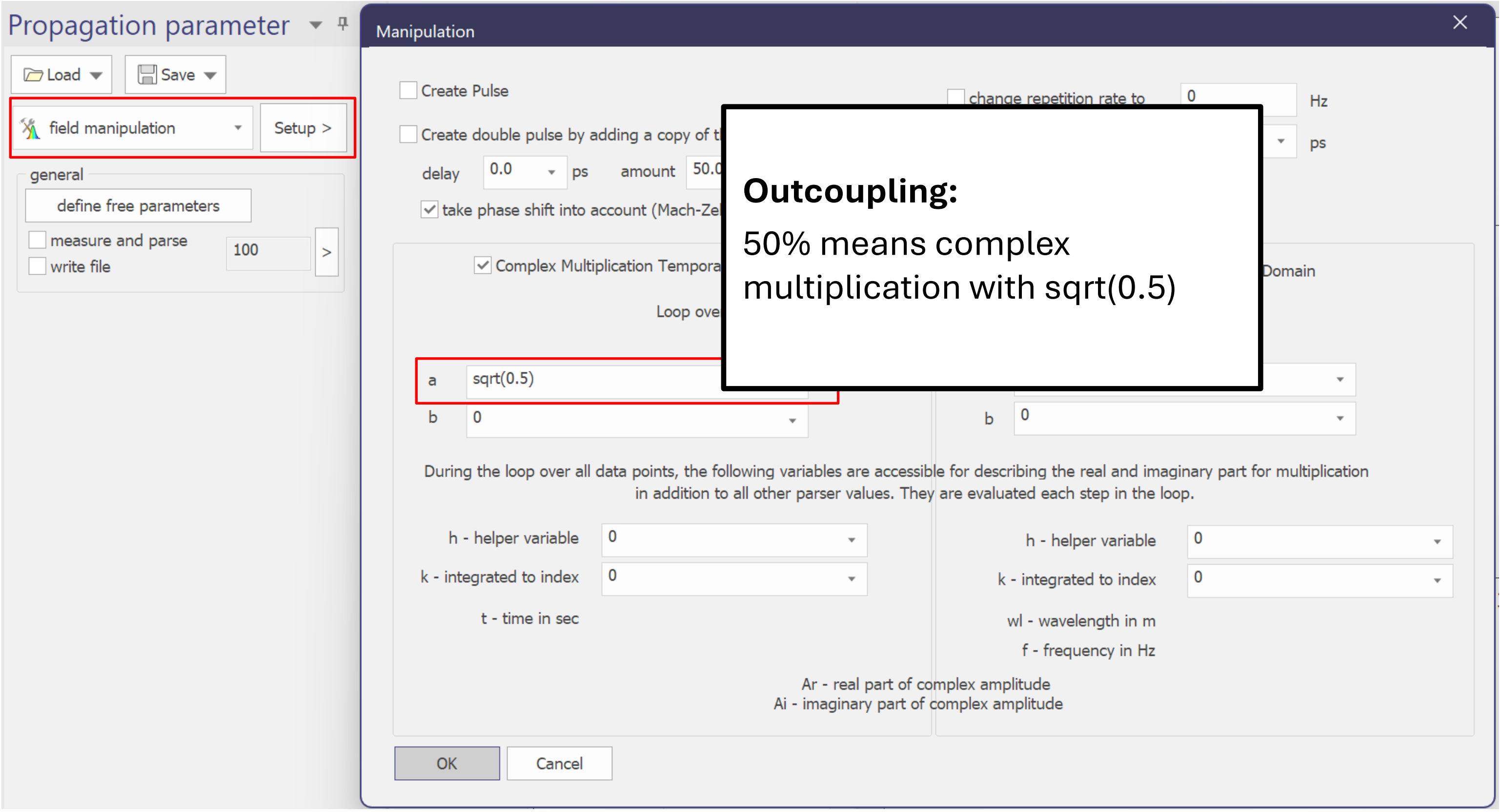


Save the element as „SA.ppfx“, as done before, for later use as an element.

Multi-Element Propagation: Short Pulse Fiber Lasers



The output coupler can be modelled by a simple field manipulation, where the field is multiplied by the outcoupling ration.



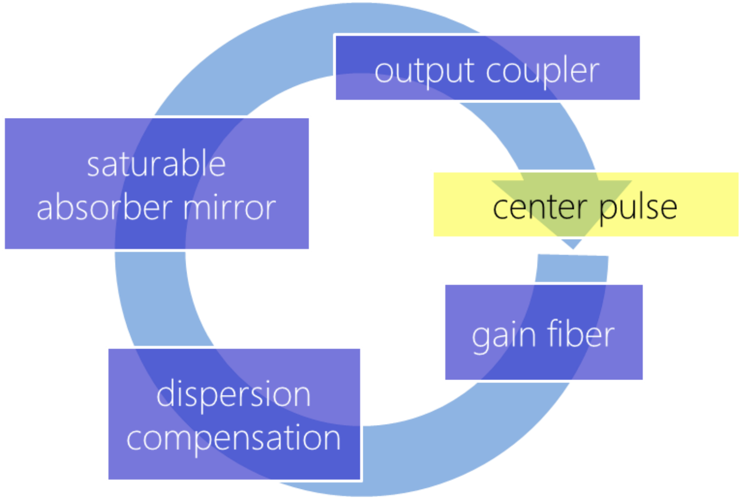
Outcoupling:

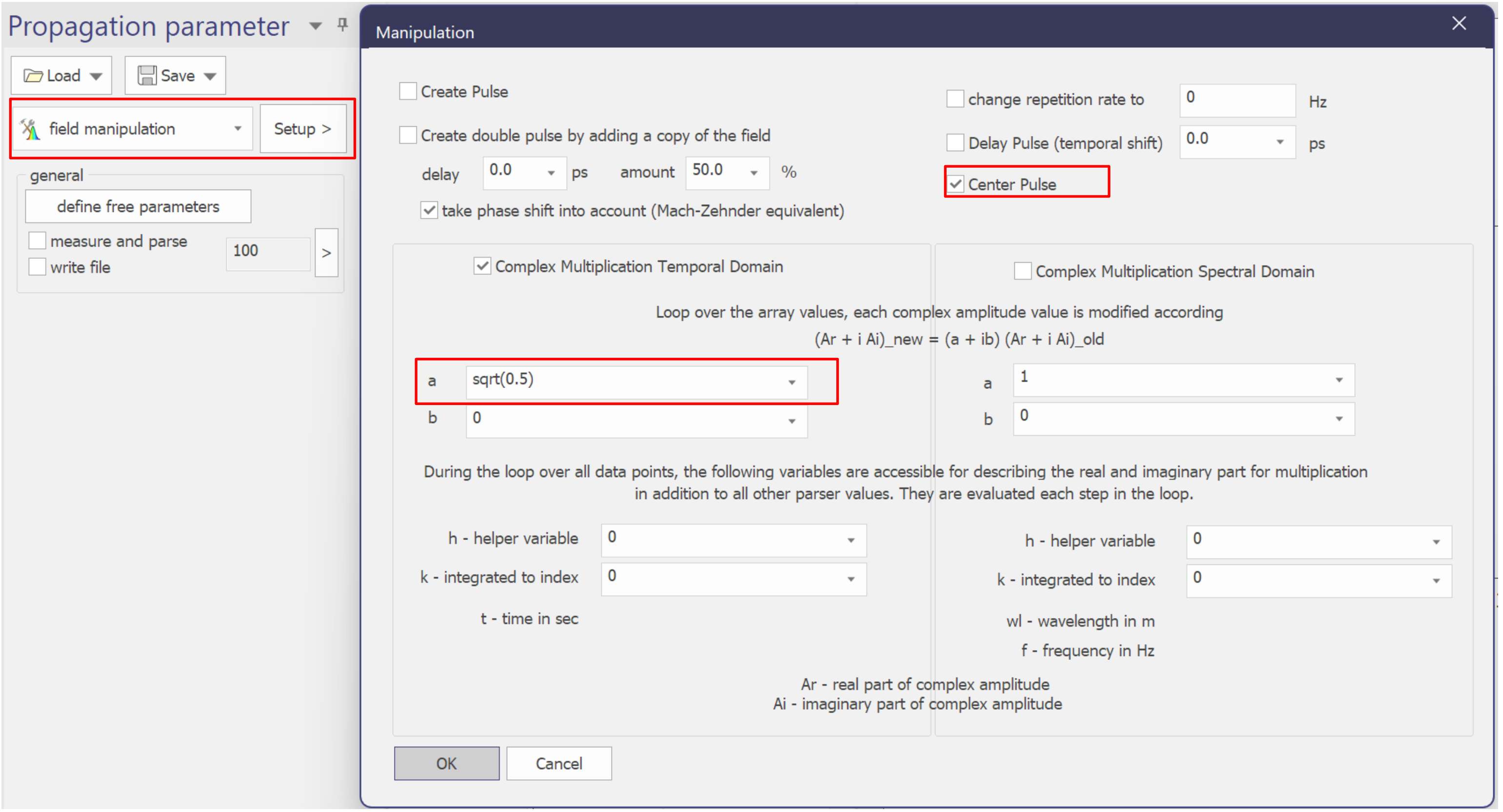
50% means complex multiplication with sqrt(0.5)

Multi-Element Propagation: Short Pulse Fiber Lasers

Centering the pulse in the time domain helps to converge the pulse, as changes are measured in the time domain. This is done in the field manipulation dialog.

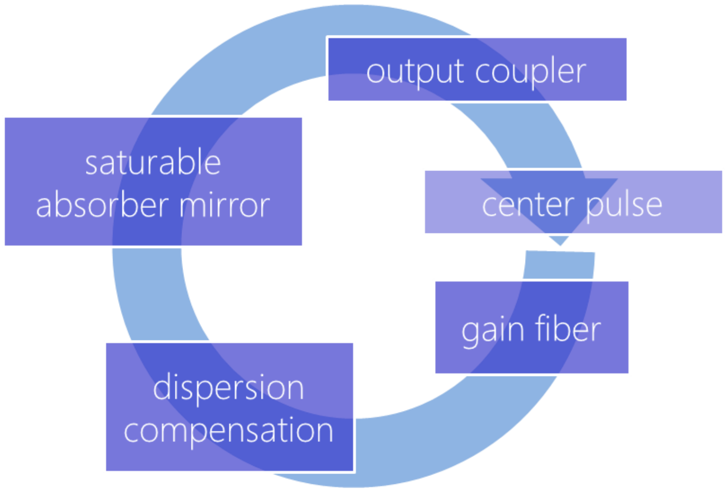
It also means that it can be combined with the field manipulation of the output coupler before in a single element. The full manipulation dialog is shown below.





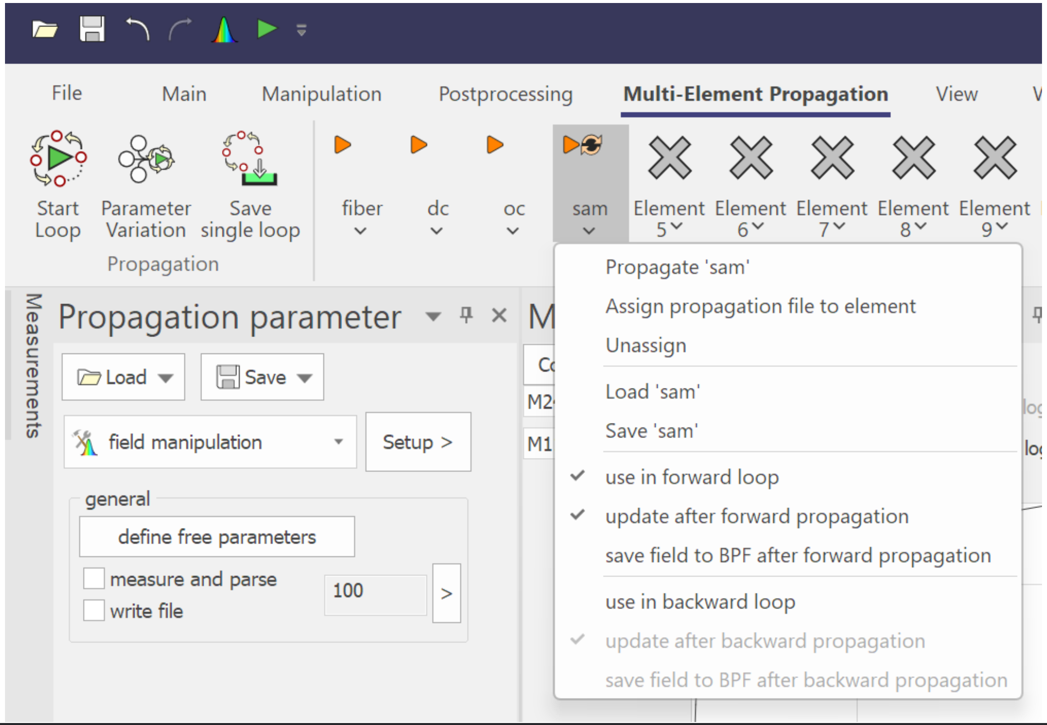
Save the element „OC.ppfx“, as done before, for later use as an element.

Multi-Element Propagation: Short Pulse Fiber Lasers

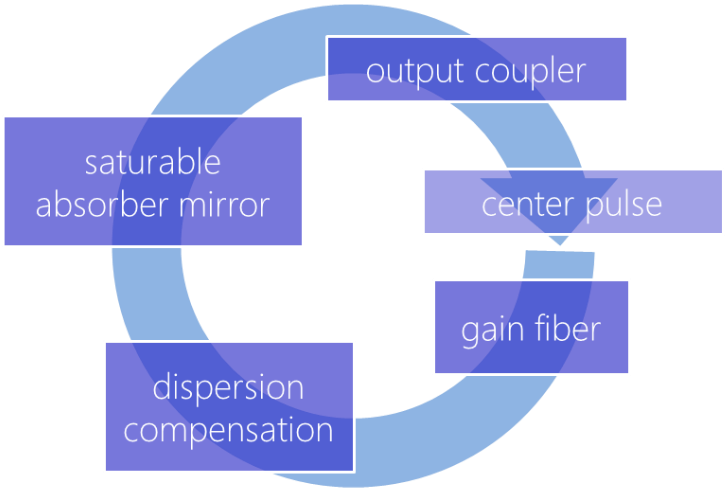


With all elements defined, let put together the multi-element propagation:

- assign all files to elements in the right order of the cavity
- Select „use in forward loop“ for all elements
- Select the last one to be updated after each loop to see convergence live during simulation
- Icons on top change according to selected status

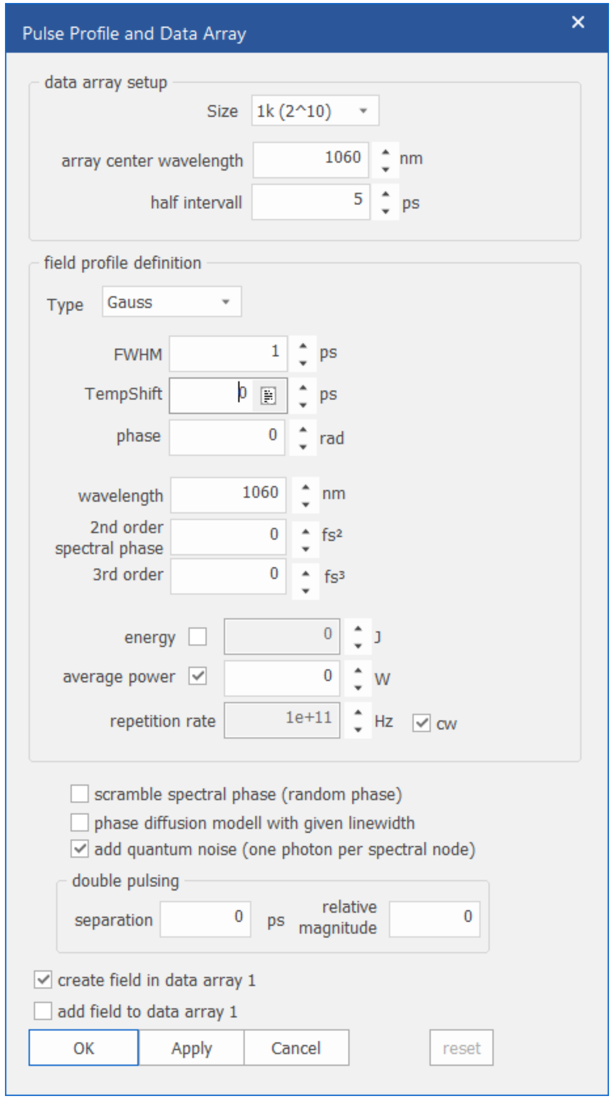


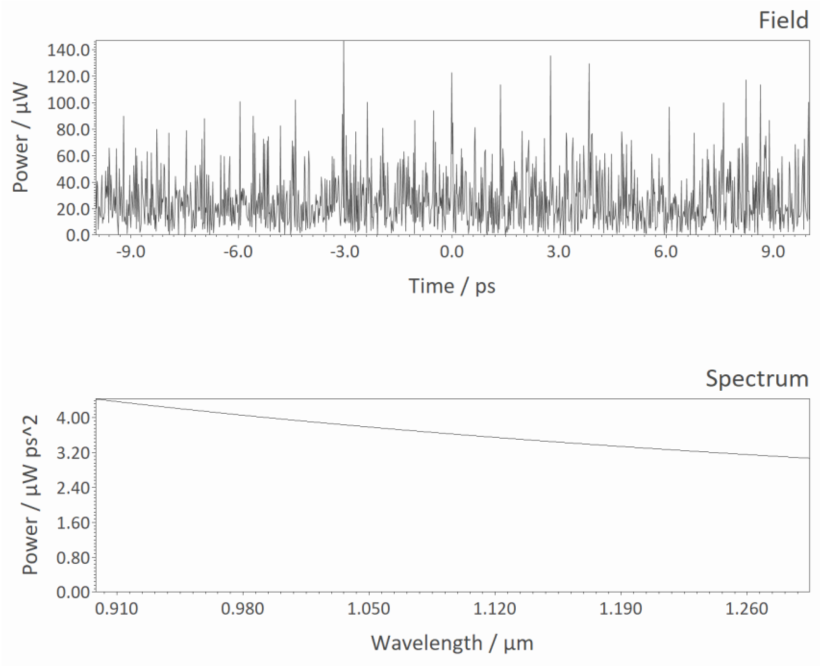
Multi-Element Propagation: Short Pulse Fiber Lasers



Before the start of the multi-element propagation, we need to define the initial conditions, that is, the field where the propagation should start.

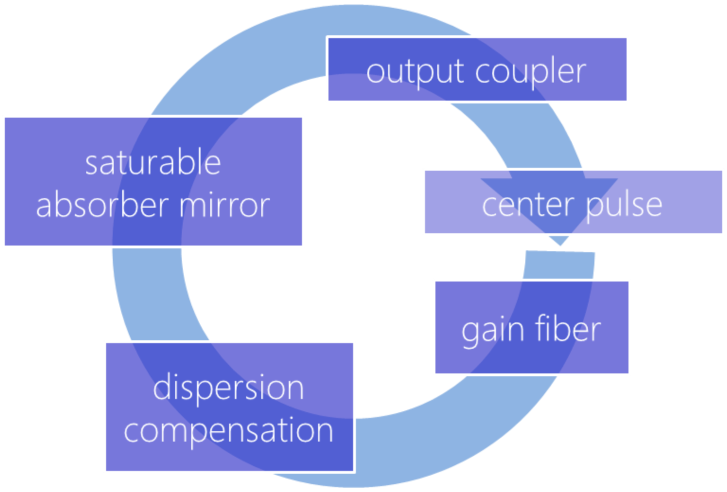
So, create the initial field with the right parameters for the final field and usually, for such short pulse oscillators, the inital condition is nothing else then quantum noise.



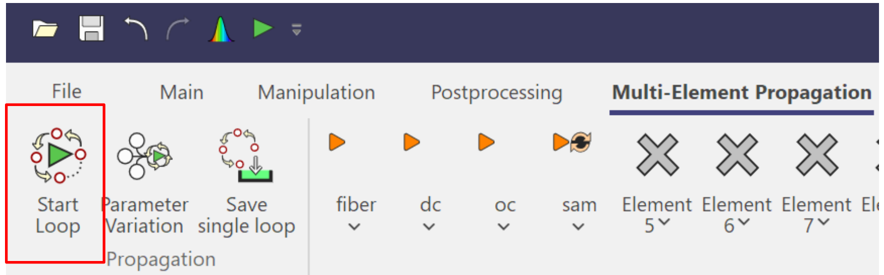


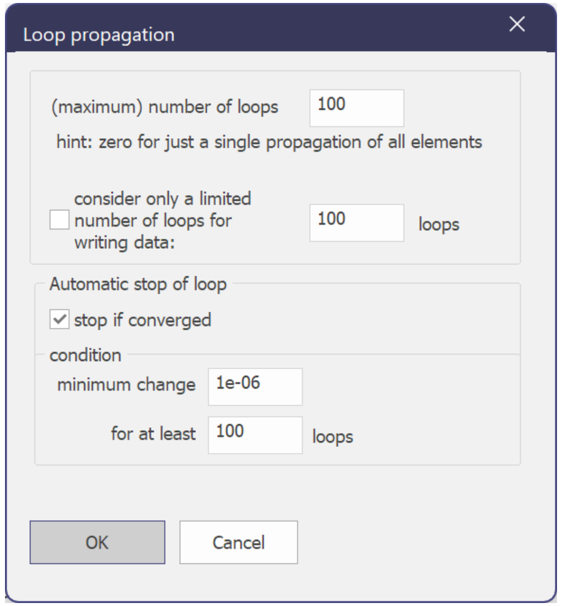
Inital field in temporal and spectrum domain.

Multi-Element Propagation: Short Pulse Fiber Lasers

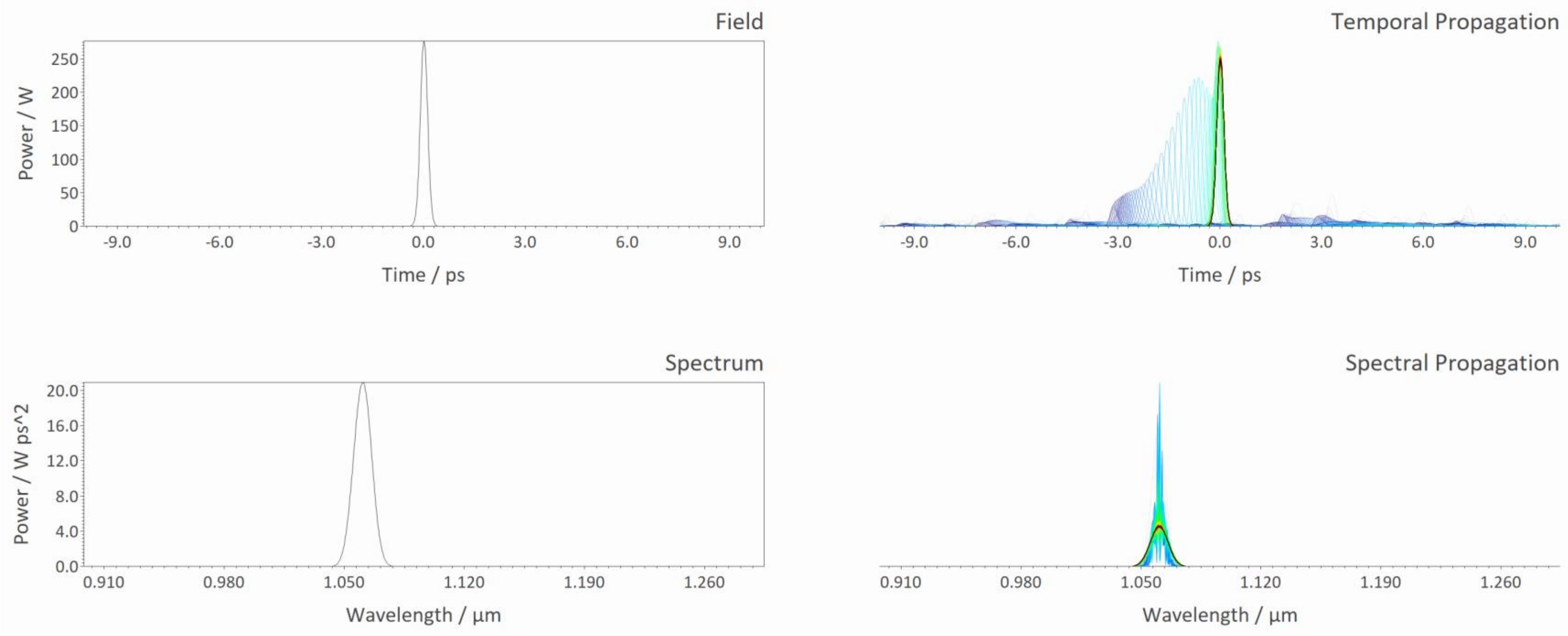


Now press „Start Loop“ with the setup dialog and press „Ok“ to let the simulation run.

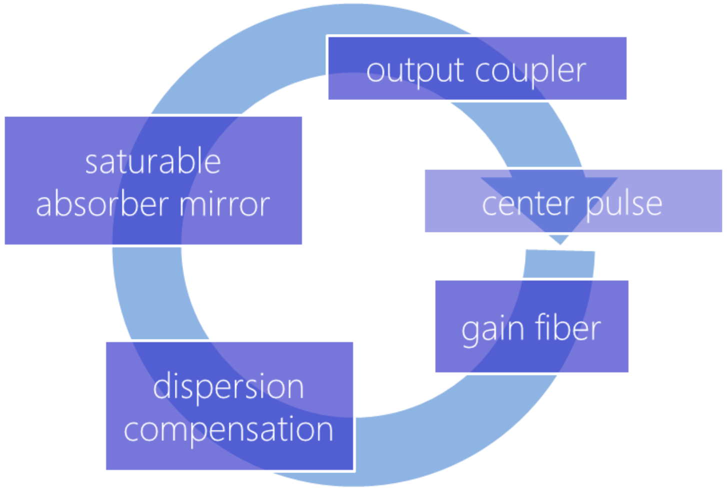




You should see, that the field and spectrum is converging to a solution that is stable:



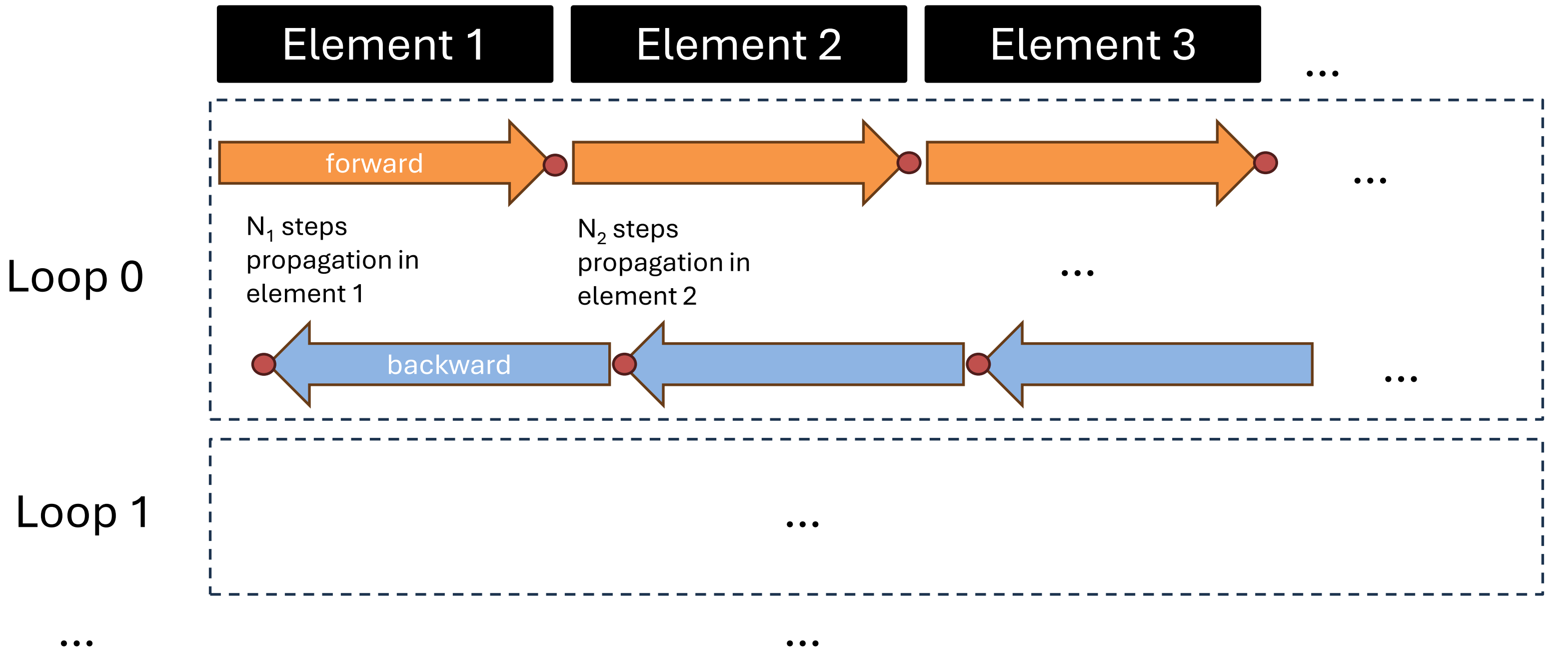
Multi-Element Propagation: Short Pulse Fiber Lasers



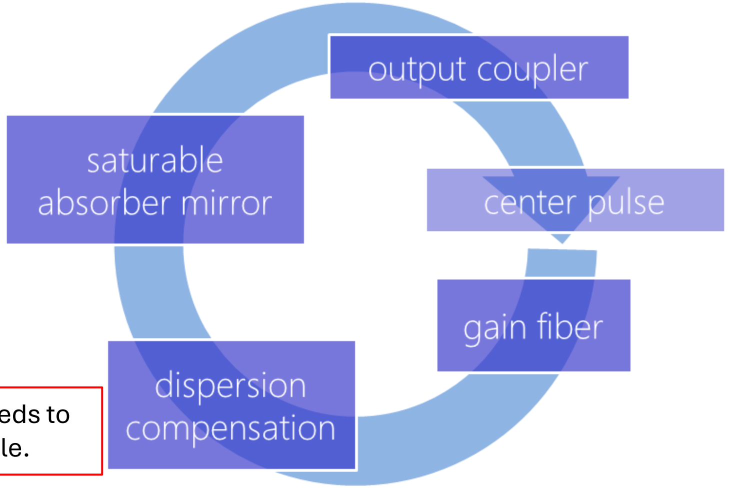
How do I get information out of the multi element propagation?

Let us first take a look at the possibilities of data along the propagation:

- Changes along each elements propagation
- Only the result at the end of each element
- Both depend on the loop count



Multi-Element Propagation: Short Pulse Fiber Lasers



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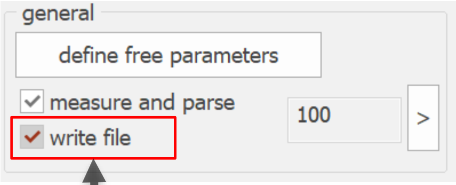
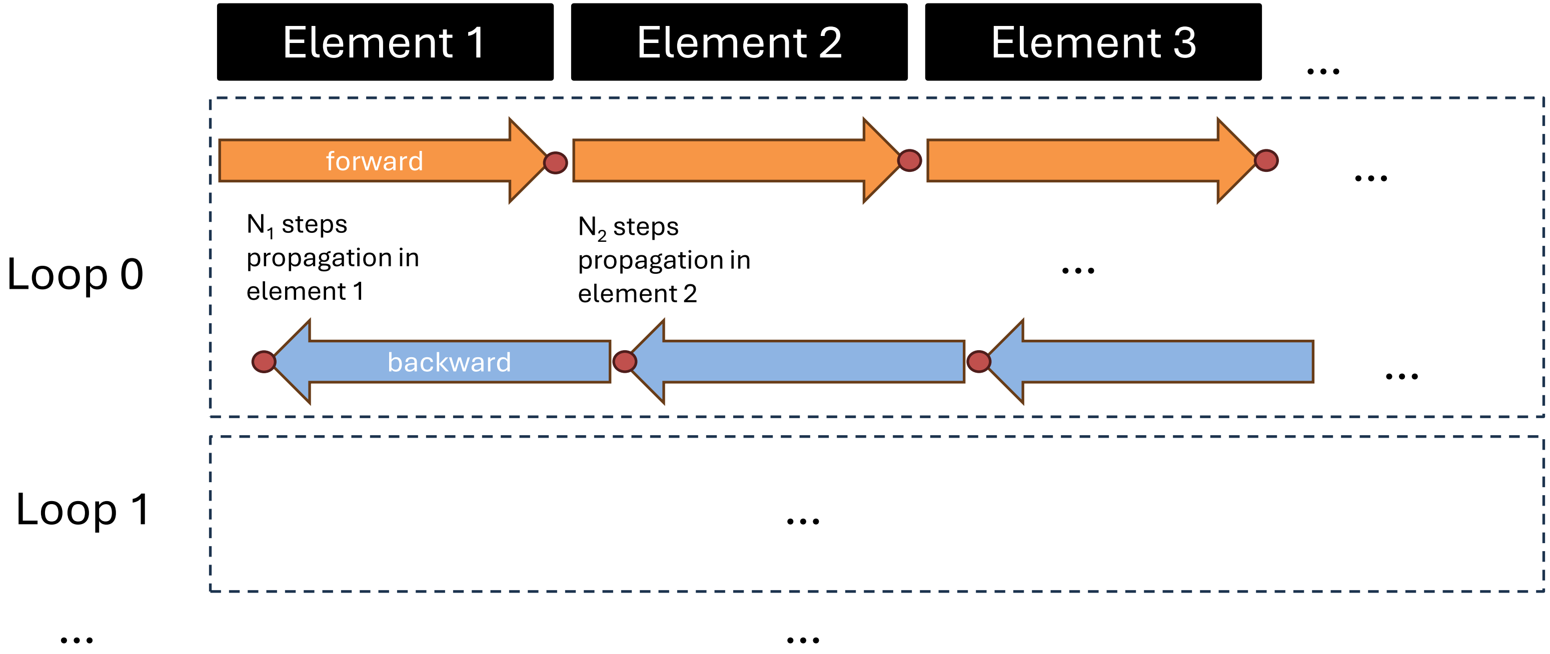


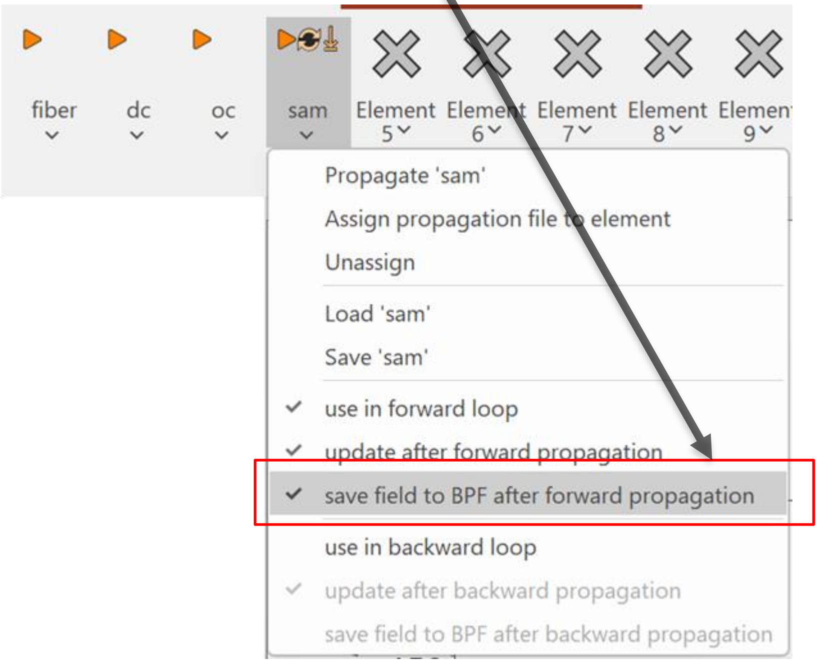
Let us first take a look at the possibilities of data along the propagation:

- Changes along each elements propagation
- Only the result at the end of each element
- Both depend on the loop count

To save the full propagation results in *each element*, „write file“ needs to be switched on and saved to the particular elements propagation file.

To save *the results after the elements*, select it in the sub-menu of the element:





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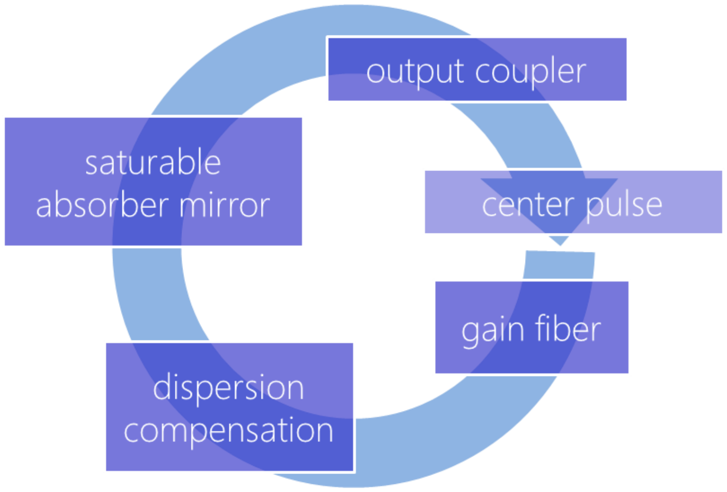


How do I get information out of the multi element propagation?

Example:

- Only the result at the end of each element

On start 

you will be asked about a filename, if not given in the dialog. Please use a filename, that is a base filename, as the element number and forward/backward signature will be attached to this base filename.

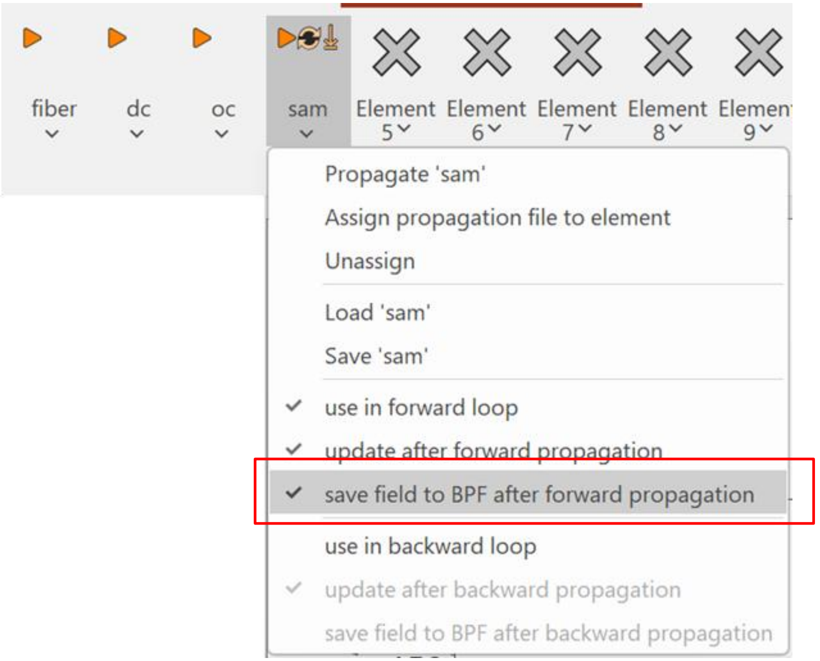
In my case, I used „after_propagation“ as the filename

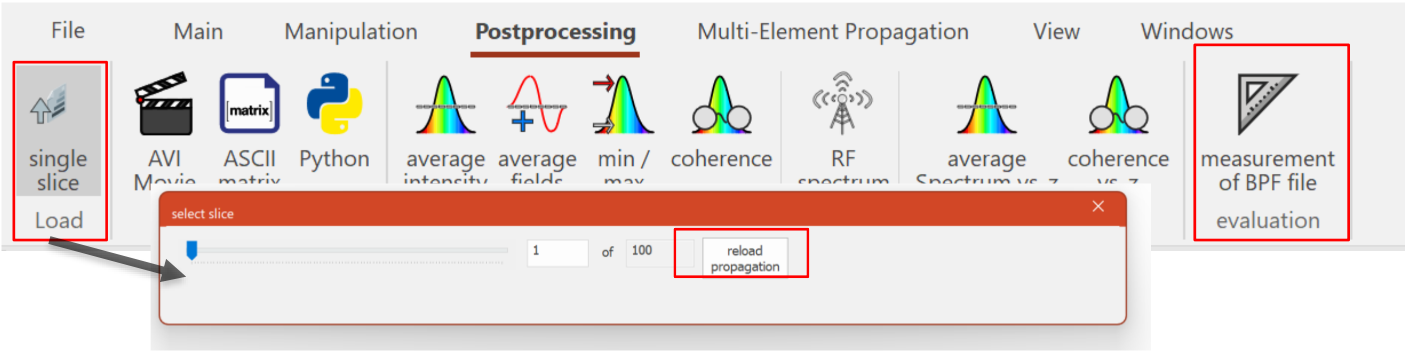
After the multi-element propagation is finished, the following file is created:

You can reload the field depending on the loop count, and also reload it into fiberdesk‘s 2D plot.

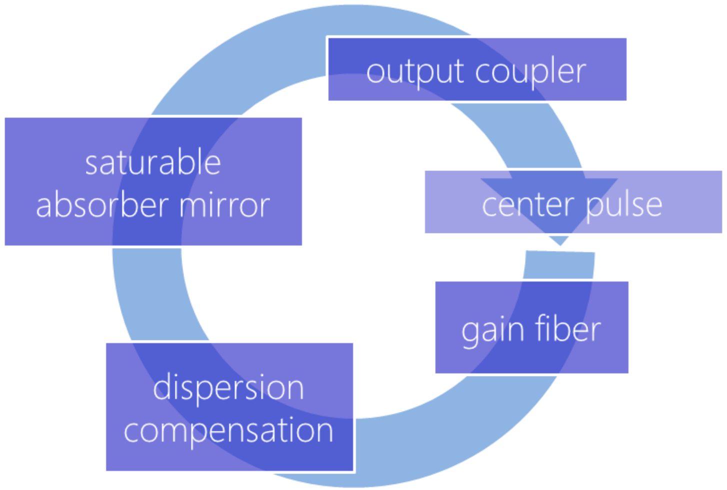
Also consider measurements with this propagation file.

To save the results after the elements, select it in the sub-menu of the element:

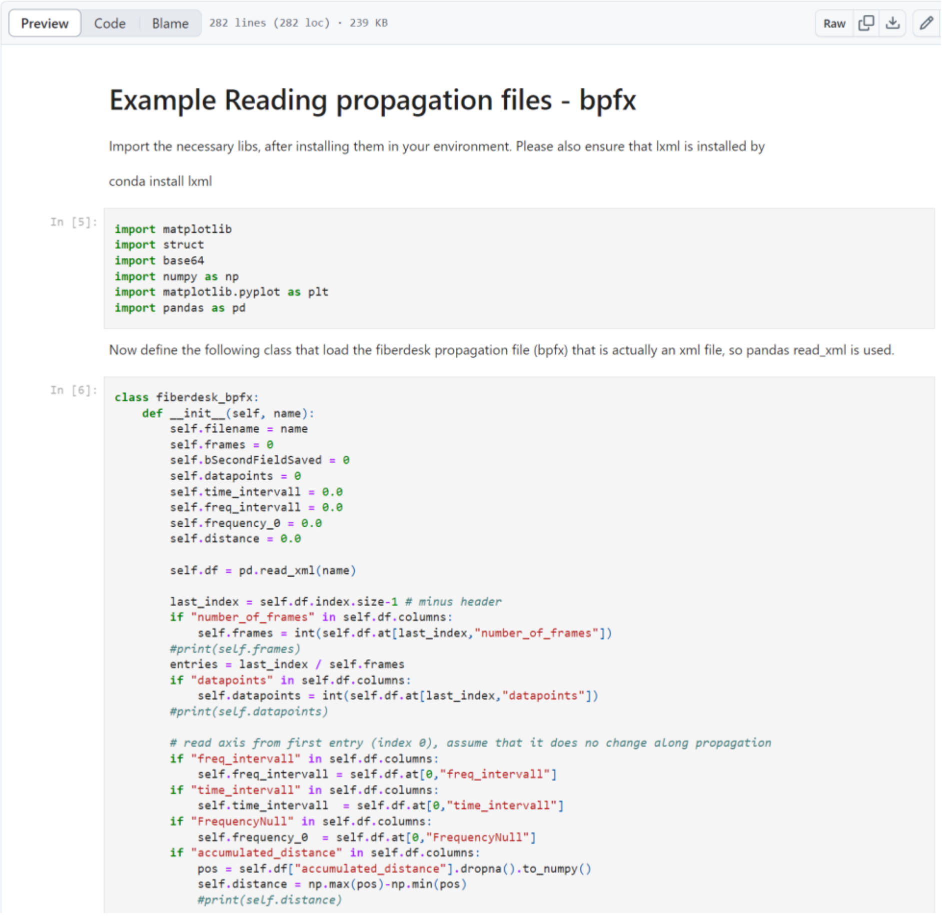




Multi-Element Propagation: Short Pulse Fiber Lasers



You can also load, display and manipulate the saved data in PYTHON. Download the python script (jupyter notebook) from the homepage to process BPFX files.



Preview | Code | Blame | 282 lines (282 loc) · 239 KB | Raw

Example Reading propagation files - bpfx

Import the necessary libs, after installing them in your environment. Please also ensure that lxml is installed by

conda install lxml

In [5]:
```python
import matplotlib
import struct
import base64
import numpy as np
import matplotlib.pyplot as plt
import pandas as pd
```

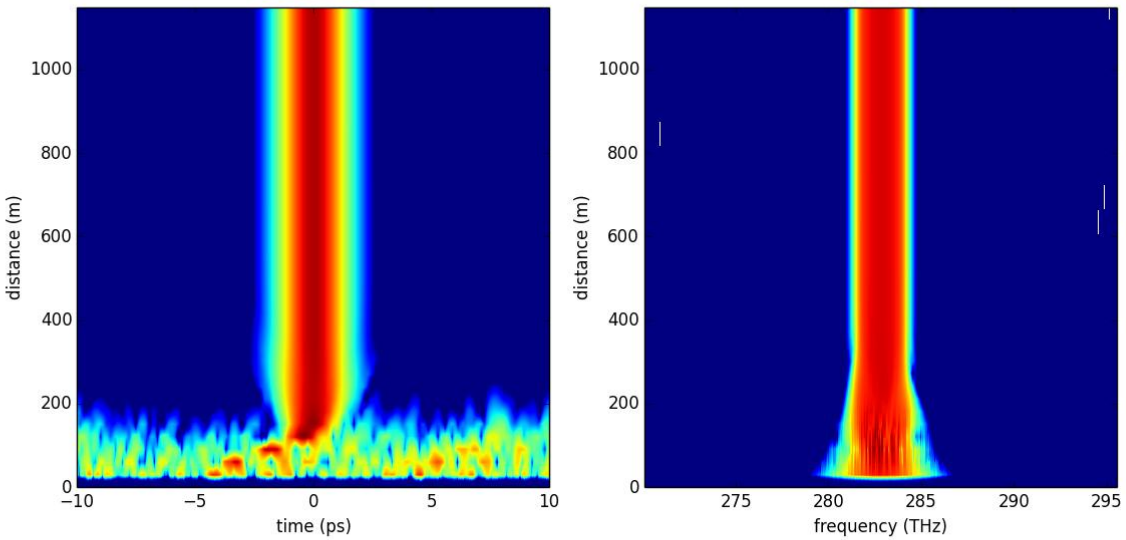
Now define the following class that load the fiberdesk propagation file (bpfx) that is actually an xml file, so pandas read_xml is used.

In [6]:
```python
class fiberdesk_bpfx:
    def __init__(self, name):
        self.filename = name
        self.frames = 0
        self.bSecondFieldSaved = 0
        self.datapoints = 0
        self.time_intervall = 0.0
        self.freq_intervall = 0.0
        self.frequency_0 = 0.0
        self.distance = 0.0

        self.df = pd.read_xml(name)

        last_index = self.df.index.size-1 # minus header
        if "number_of_frames" in self.df.columns:
            self.frames = int(self.df.at[last_index,"number_of_frames"])
        #print(self.frames)
        entries = last_index / self.frames
        if "datapoints" in self.df.columns:
            self.datapoints = int(self.df.at[last_index,"datapoints"])
        #print(self.datapoints)

        # read axis from first entry (index 0), assume that it does no change along propagation
        if "freq_intervall" in self.df.columns:
            self.freq_intervall = self.df.at[0,"freq_intervall"]
        if "time_intervall" in self.df.columns:
            self.time_intervall  = self.df.at[0,"time_intervall"]
        if "FrequencyNull" in self.df.columns:
            self.frequency_0  = self.df.at[0,"FrequencyNull"]
        if "accumulated_distance" in self.df.columns:
            pos = self.df["accumulated_distance"].dropna().to_numpy()
            self.distance = np.max(pos)-np.min(pos)
            #print(self.distance)
```



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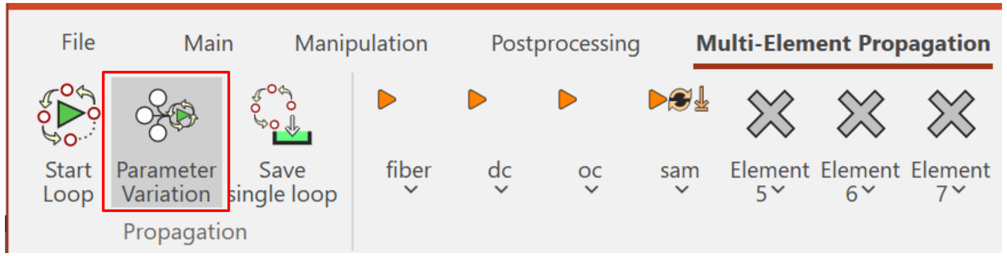
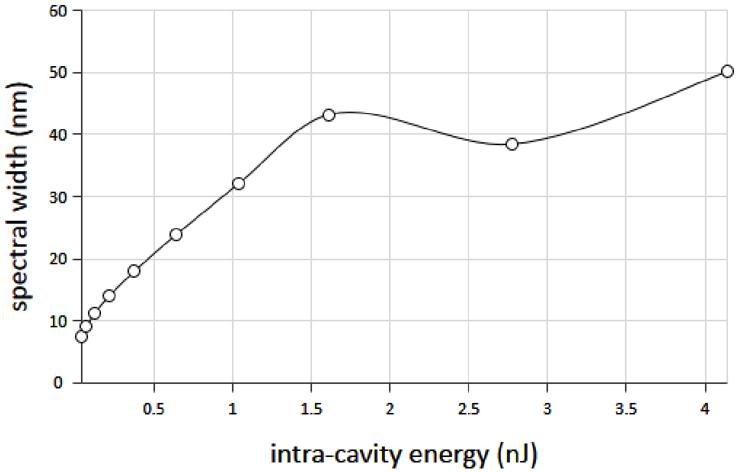
Multi-Element Propagation:

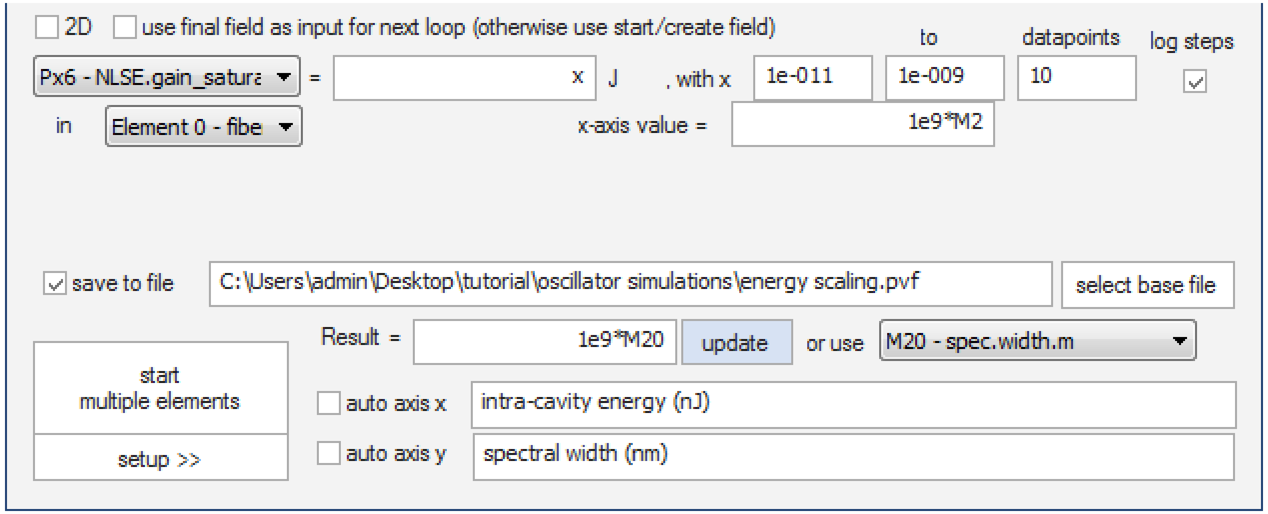
Example: Short Pulse Fiber Lasers



Multi-element > Parameter variation

we change the gain saturation to increase the energy (remark: intracavity energy!)





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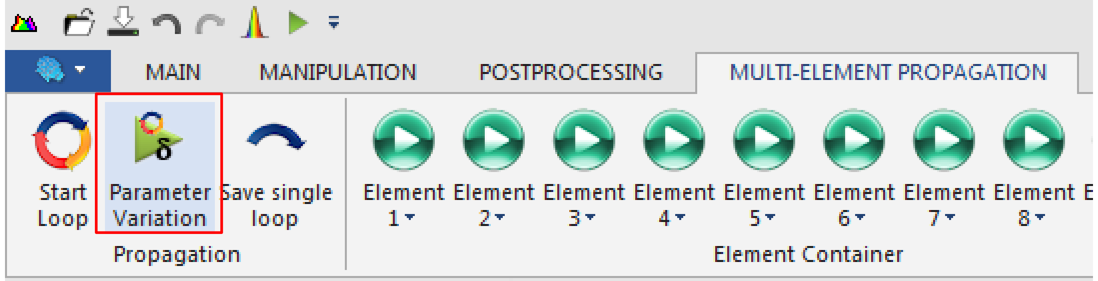

Multi-Element Propagation:

Example: Short Pulse Fiber Lasers

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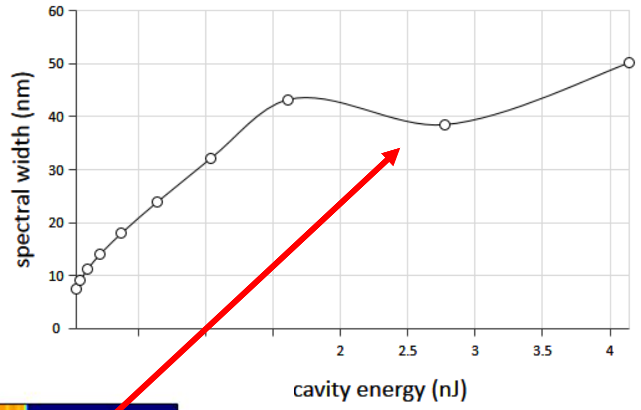

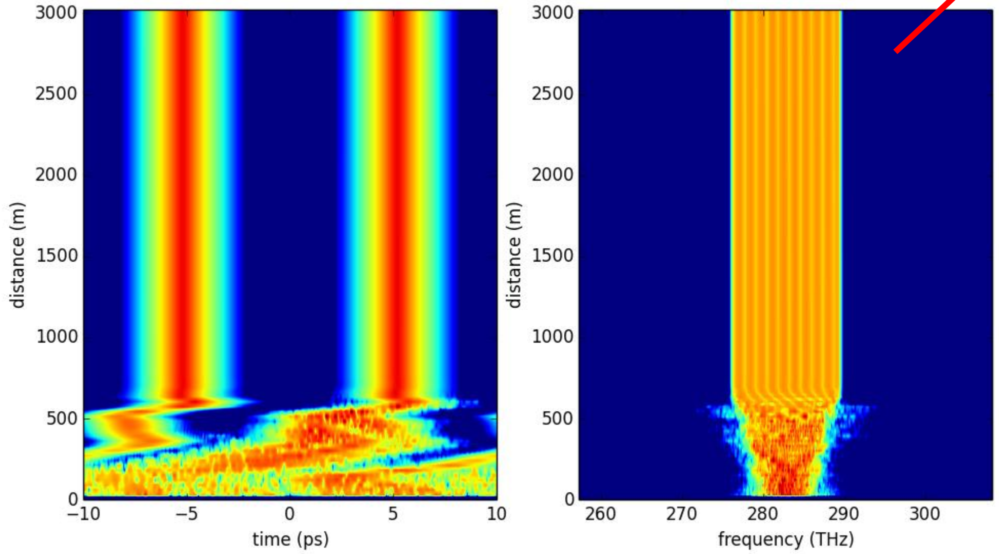

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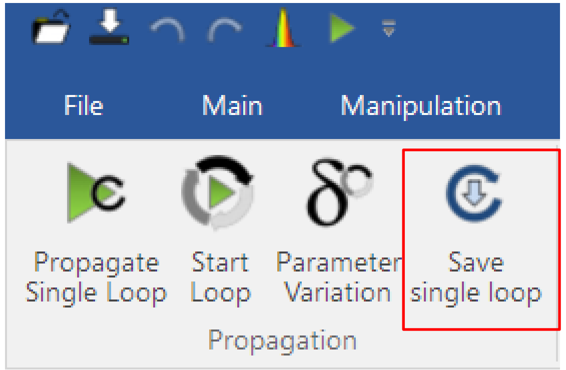
Multi-Element Propagation:

Example: Short Pulse Fiber Lasers

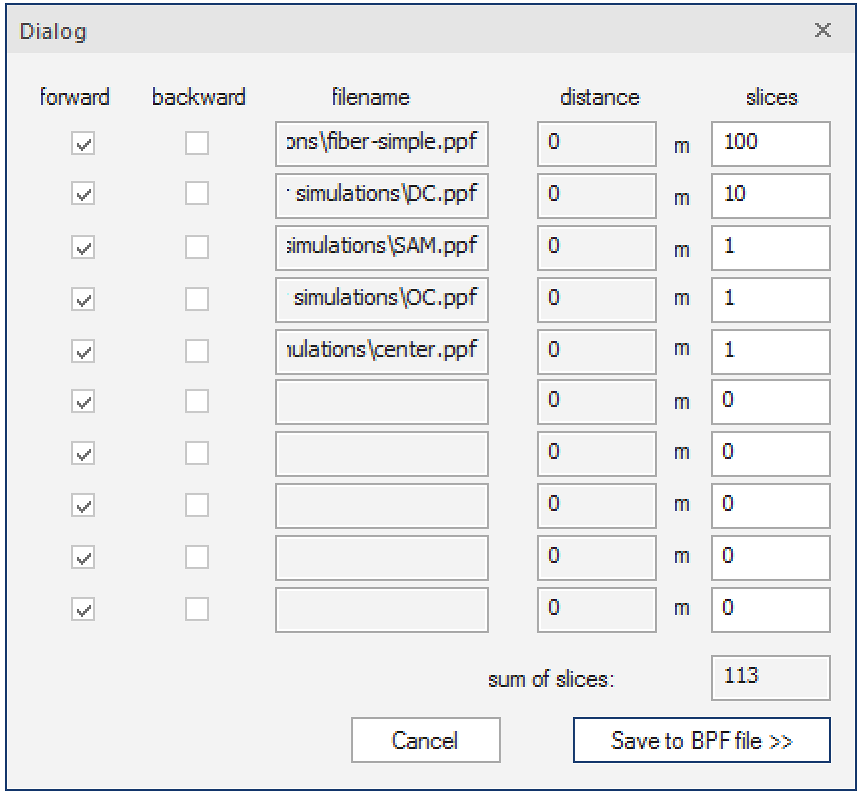


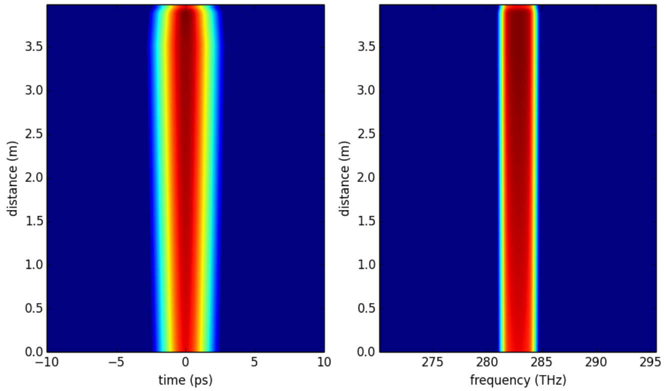
Intracavity evolution

(1) select stable solution from saved file

(2) specify slices to be saved

(3) post-process





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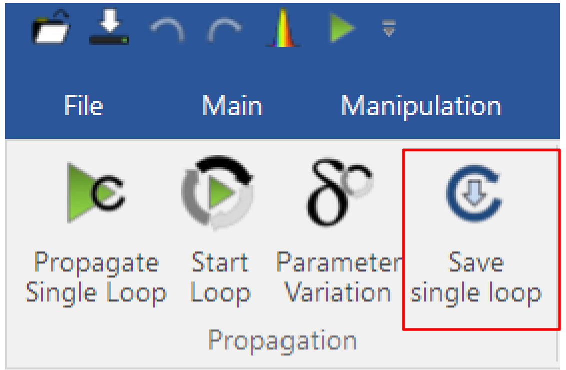
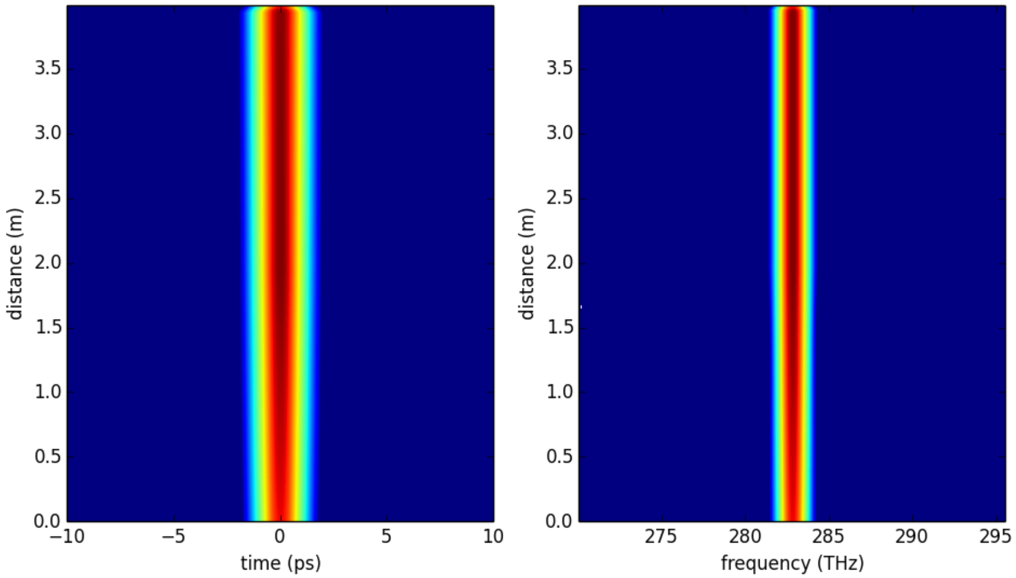
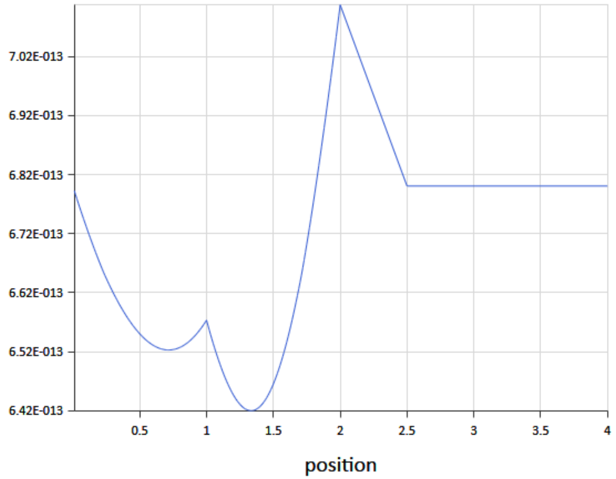
Multi-Element Propagation:

Example: Short Pulse Fiber Lasers

soliton solution: beta2@DC = -0.06 ps^2







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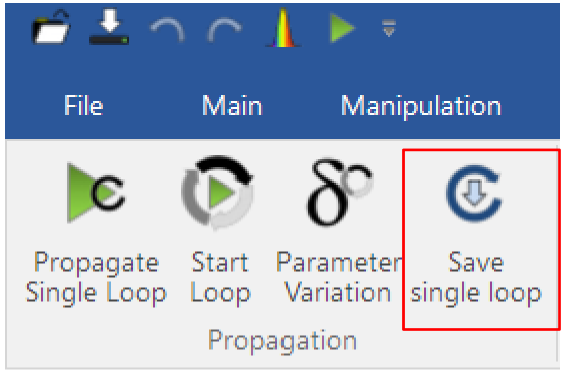
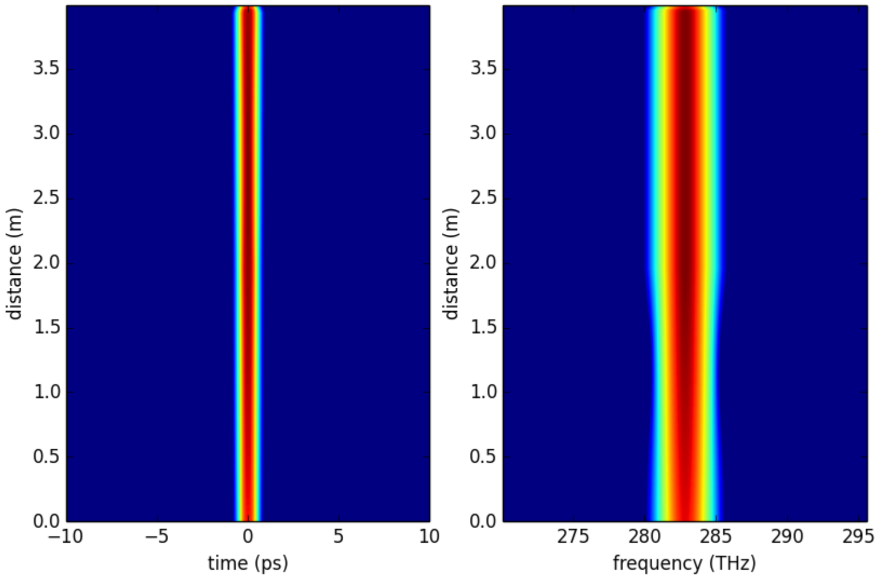
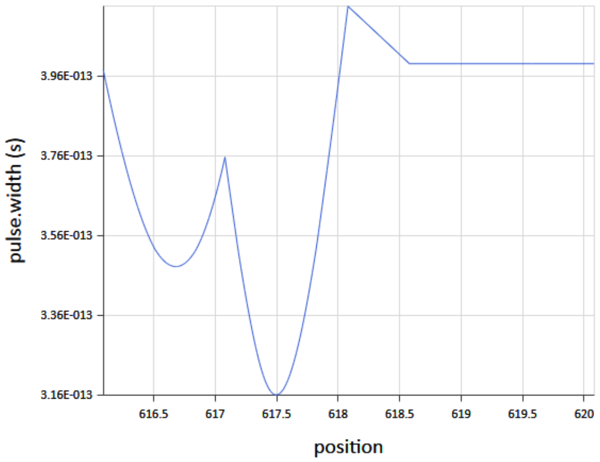
Multi-Element Propagation:

Example: Short Pulse Fiber Lasers

soliton solution: beta2@DC = -0.04 ps^2







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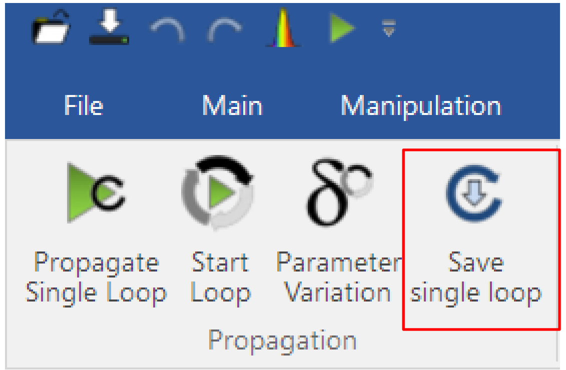
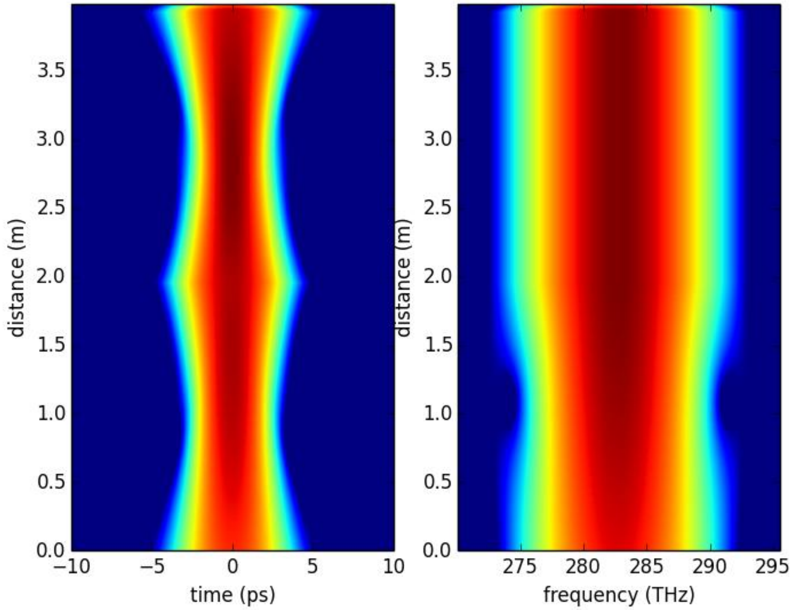
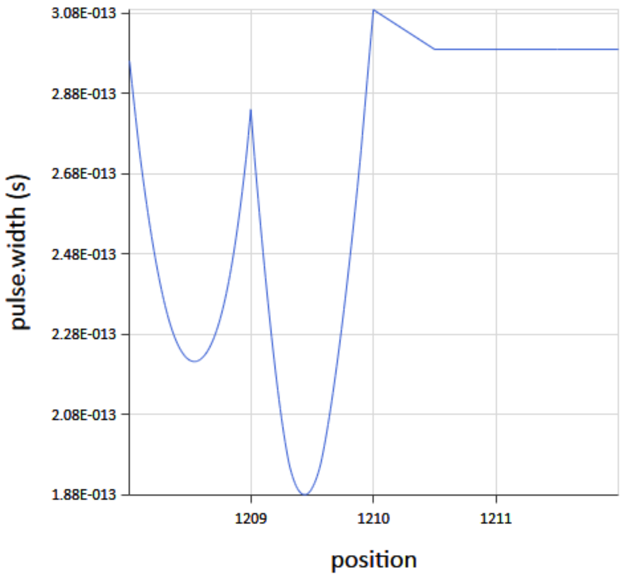
Multi-Element Propagation:

Example: Short Pulse Fiber Lasers

toward stretched pulse: beta2@DC = -0.03 ps^2







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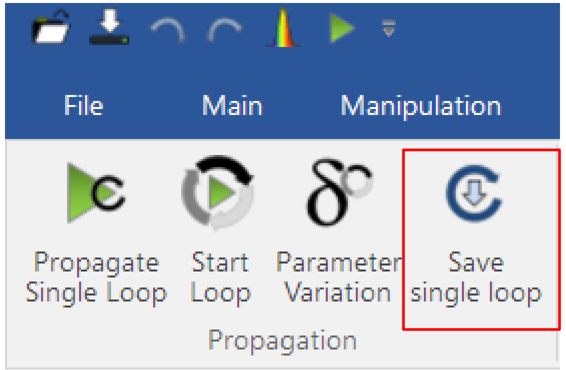
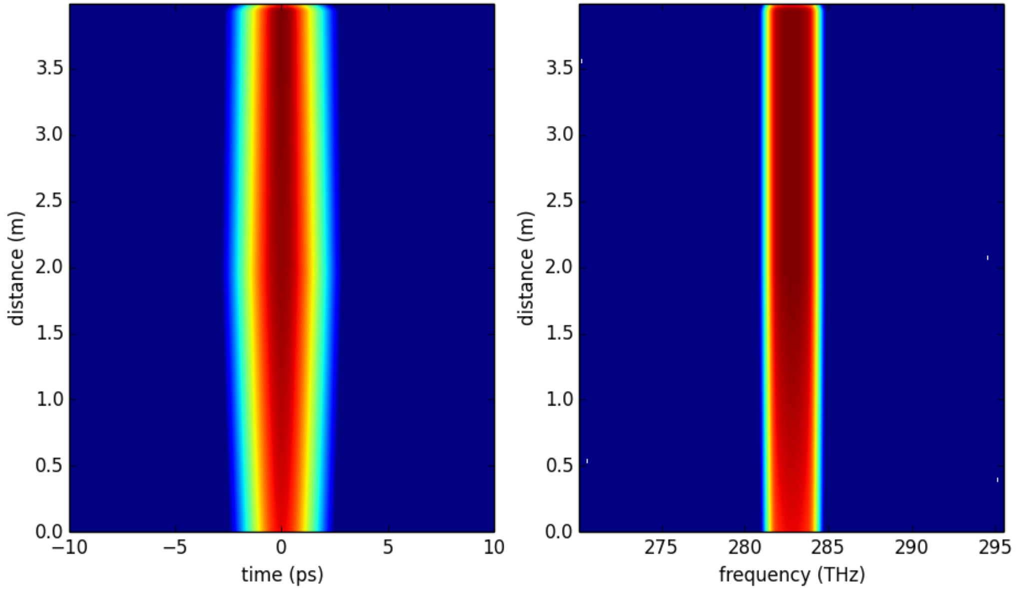
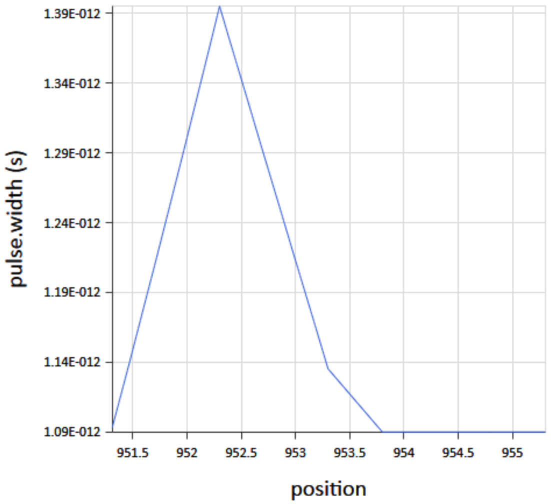
Multi-Element Propagation:

Example: Short Pulse Fiber Lasers

similariton: beta2@DC = -0.02 ps^2





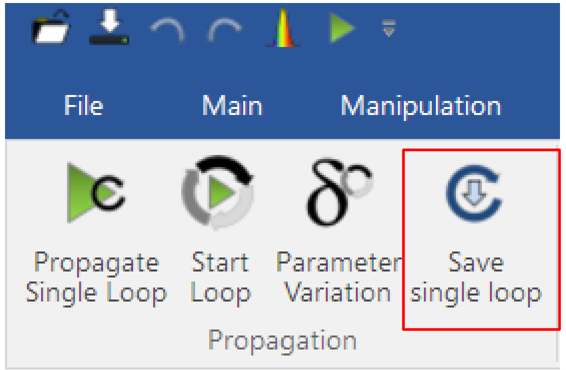


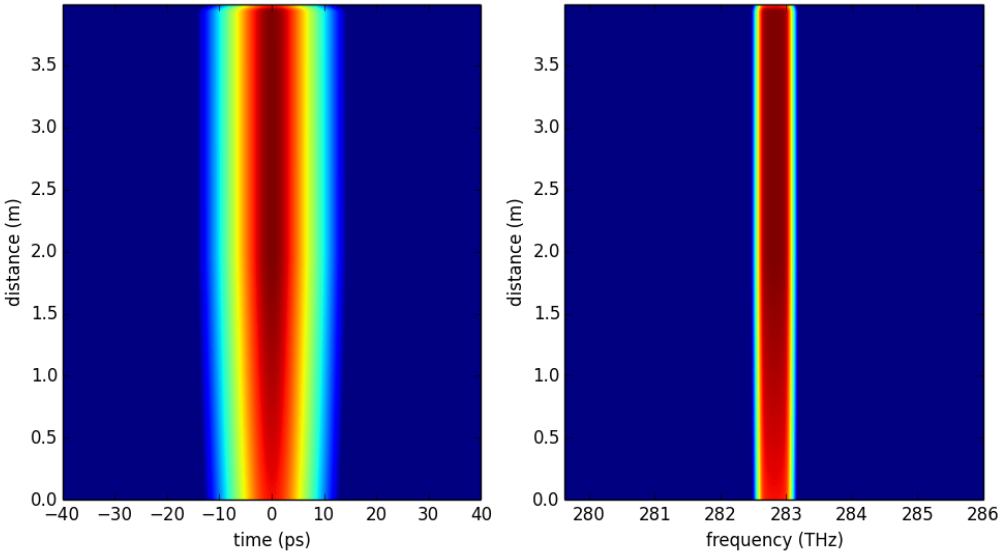
lecture 5

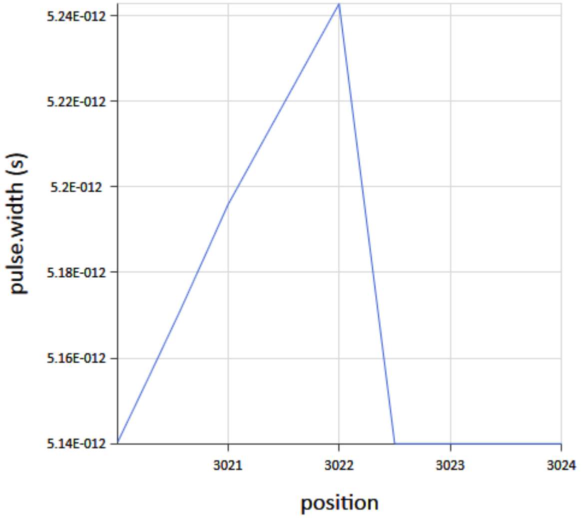
Multi-Element Propagation:

Example: Short Pulse Fiber Lasers

chirped pulse oscillator: beta2@DC = +0.02 ps^2







Lecture 5

Multi-Element Propagation

Part 1:

Short Pulse Fiber Laser

Part 2:

Mamyshev Oscillator

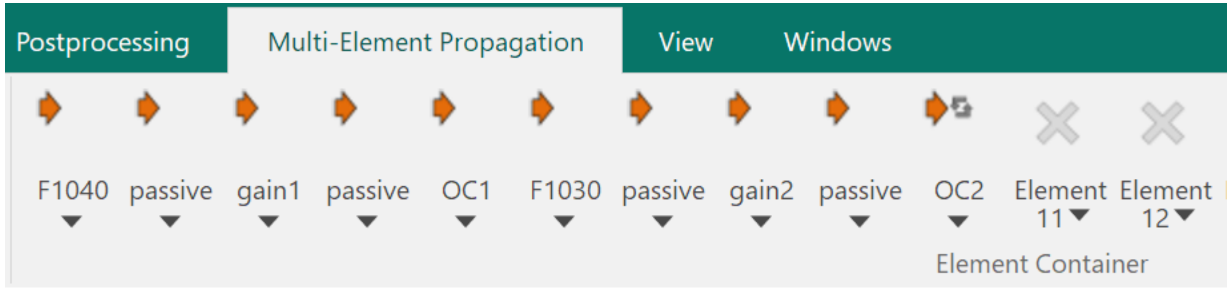
Part 3:

Micro Comb Generator

Multi-Element Propagation: Mamyshev Oscillator

See Z. Liu, Z. Ziegler, L. G. Wright, and F. W. Wise. "Megawatt peak power from a Mamyshev oscillator." Optica **4**, 649 (2017).

The model of the Mamyshev oscillator is using the following elements:



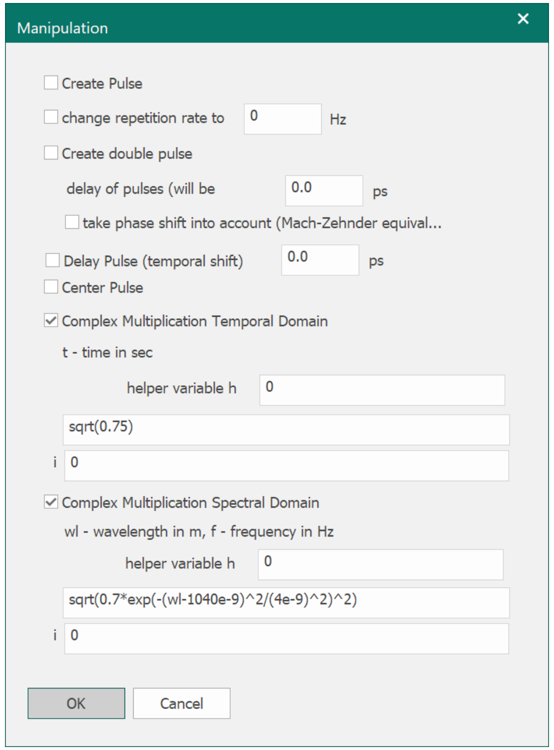
It uses two separated filters at 1030 nm and 1040 nm as well as passive and active fibers in between. The gain fibers are different after the filter. An output coupler is used at the end.

Multi-Element Propagation: Mamyshev Oscillator

The filters are defined as follows:

Pulse manipulation propagation

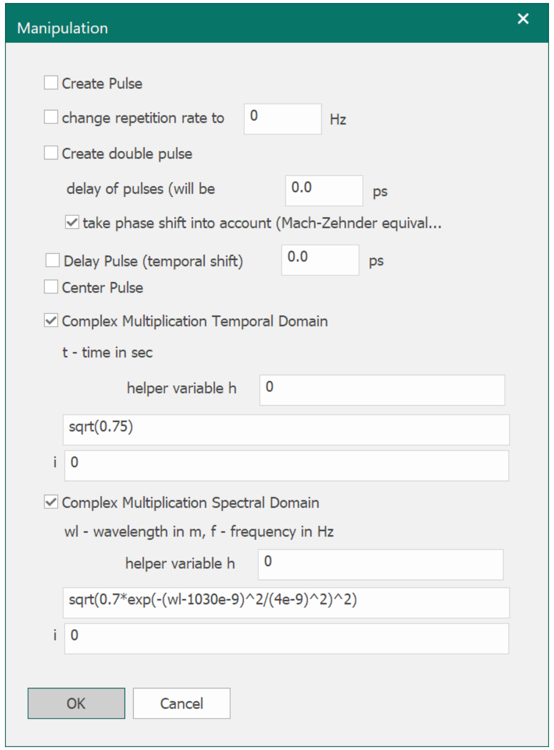
Saved as: 1040.ppf



Contains a general loss of 25 % and a filter transmission of 70%. The width ($1/e^2$) is 4 nm centered at 1040 nm.

Pulse manipulation propagation

Saved as: 1030.ppf

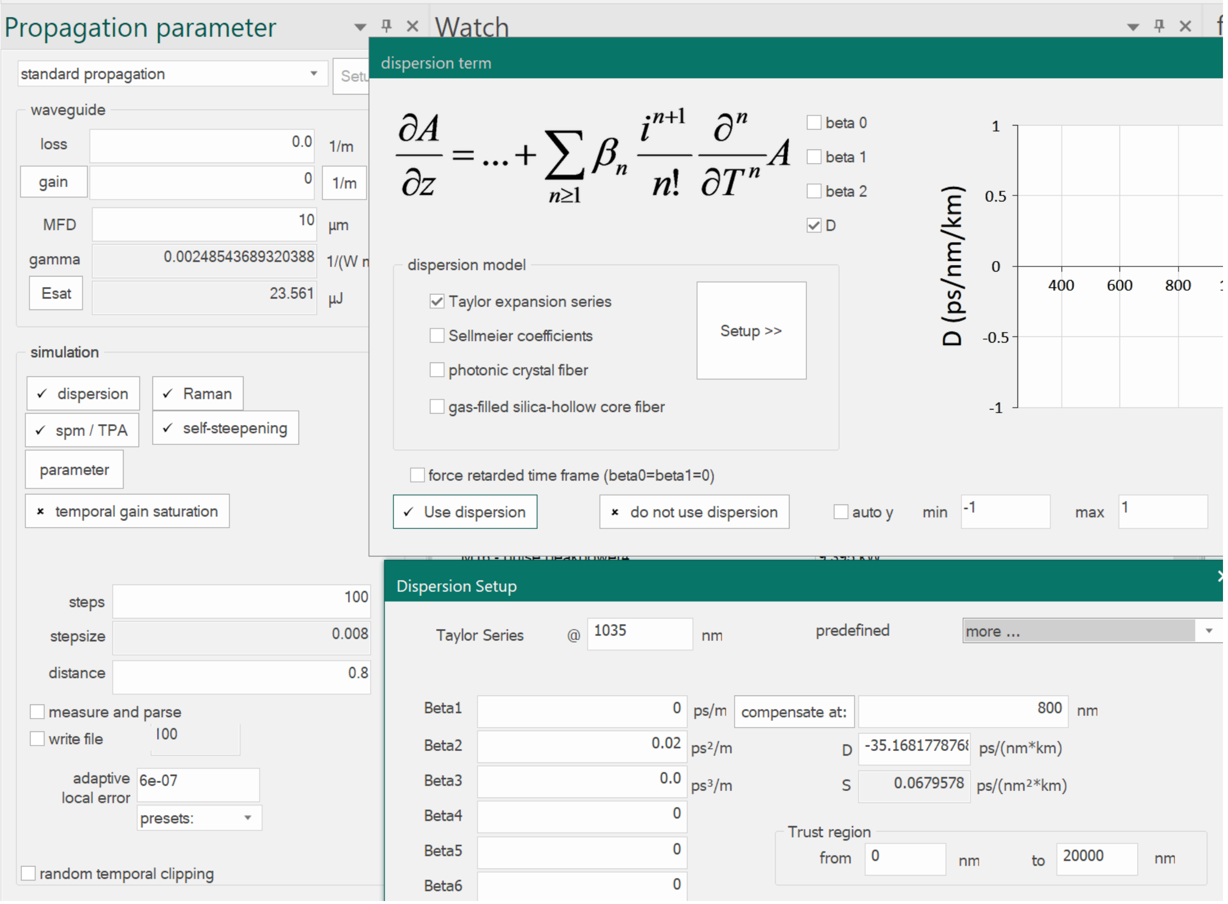


Similar, but centered at 1030 nm.

Multi-Element Propagation: Mamyshev Oscillator

The passive fiber is defined as a standard propagation. The dispersion is only second order at 1035 nm.

standard propagation
Saved as: passive.ppf

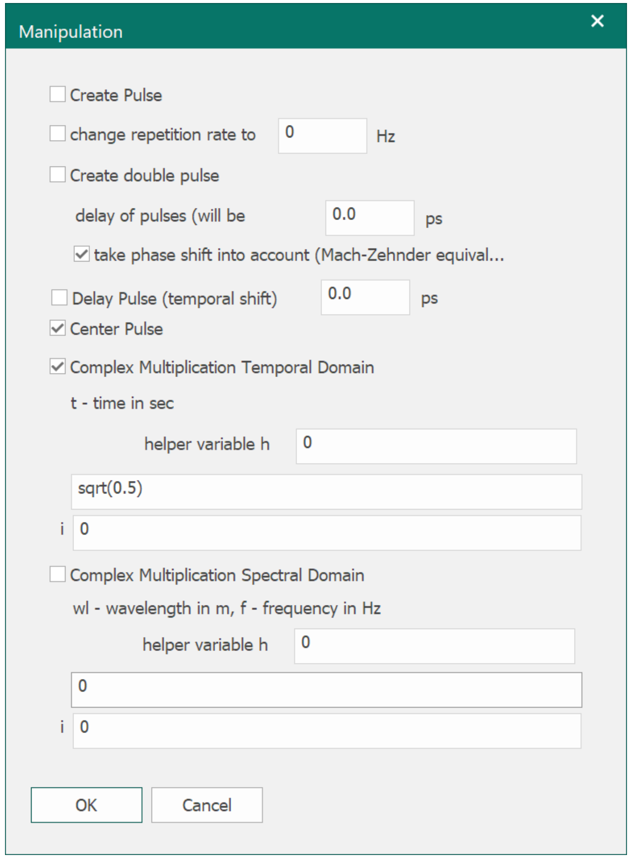


$$\frac{\partial A}{\partial z} = \ldots + \sum_{n\geq 1} \beta_n \frac{i^{n+1}}{n!} \frac{\partial^n}{\partial T^n} A$$

Multi-Element Propagation: Mamyshev Oscillator

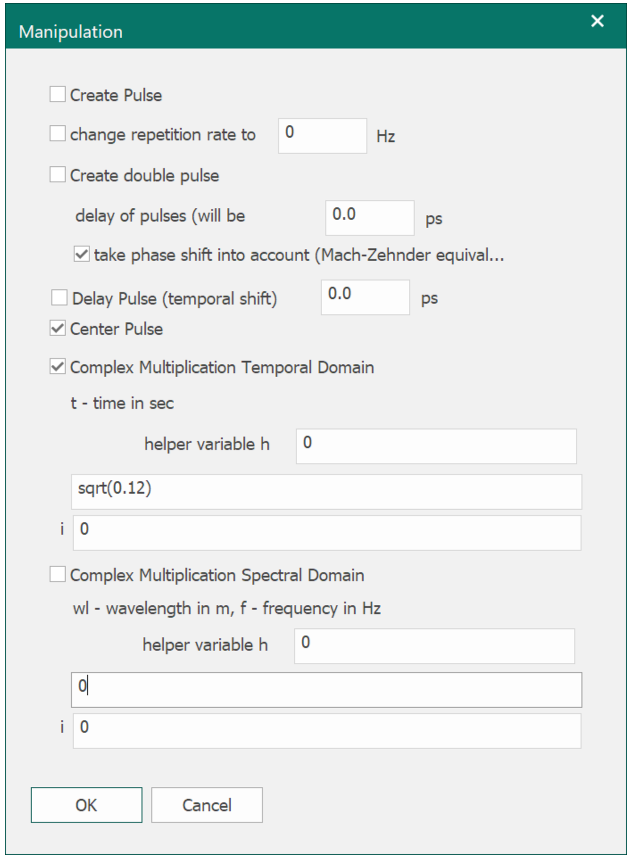
The output coupler is again defined as a pulse manipulation:

Pulse manipulation propagation
Saved as: OC1.ppf



50% Transmission.

Pulse manipulation propagation
Saved as: OC2.ppf

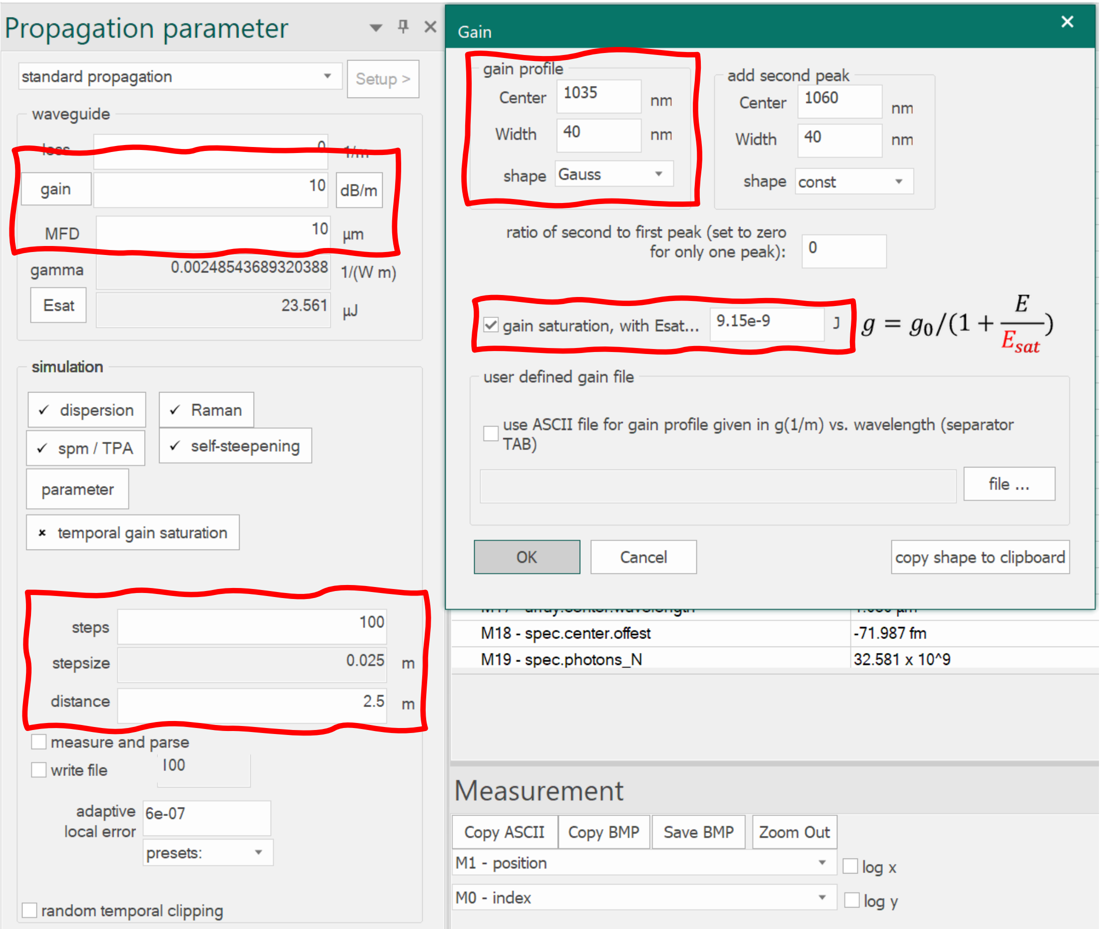


12% Transmission. (88% out-coupling)

Multi-Element Propagation: Mamyshev Oscillator

The first gain fiber is defined as a standard propagation:

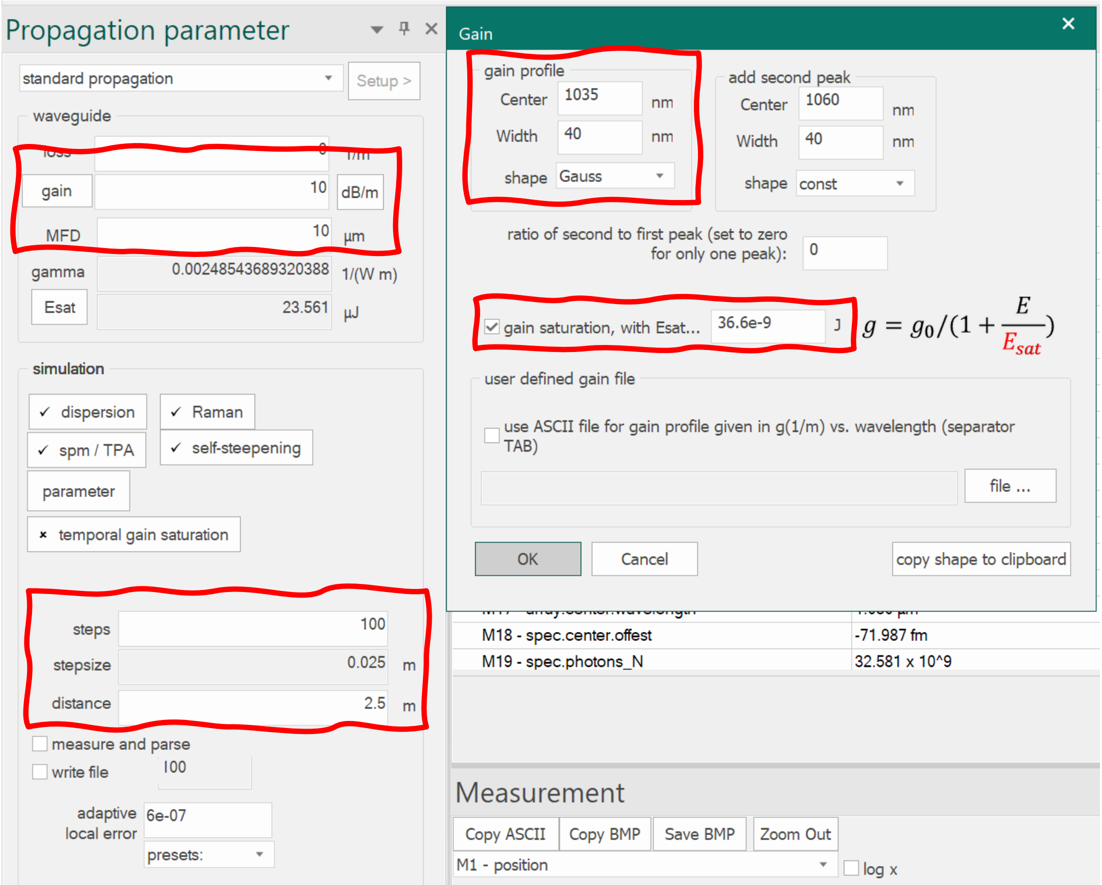
Standard propagation
Saved as: gain1.ppf



Multi-Element Propagation: Mamyshev Oscillator

The second gain fiber is defined as a standard propagation:

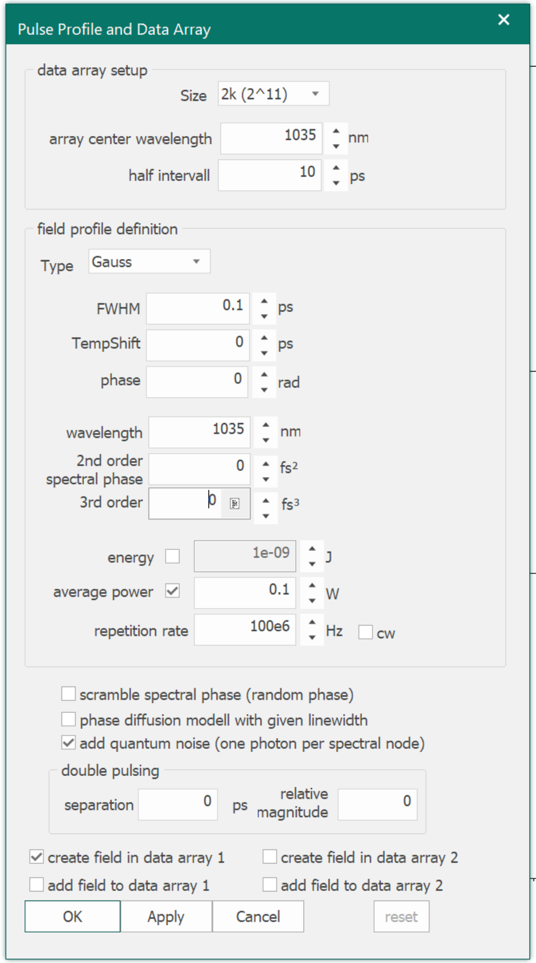
Standard propagation
Saved as: gain2.ppf

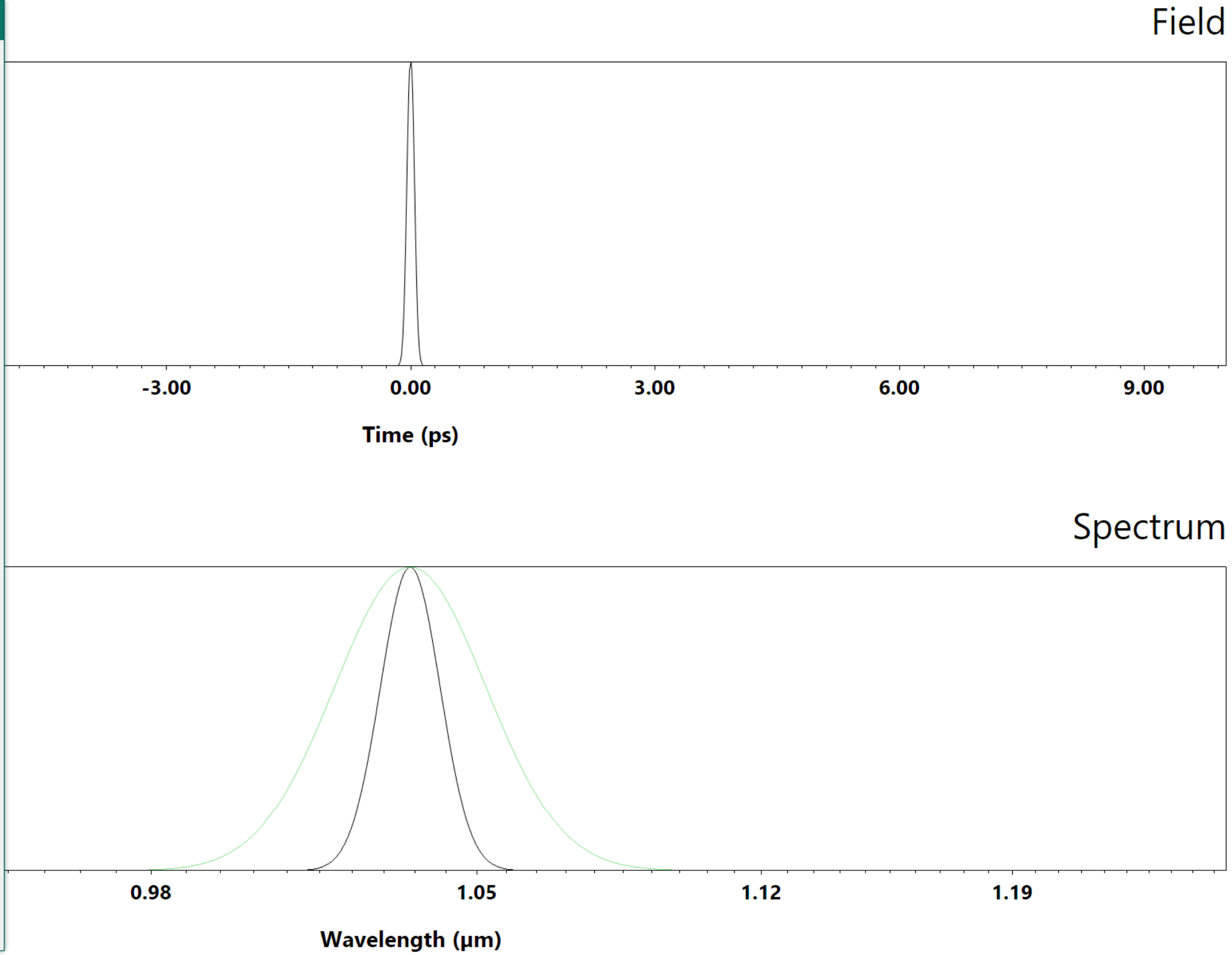


Multi-Element Propagation: Mamyshev Oscillator

As most Mamychev oscillators are not self starting, we seed with a short pulse:

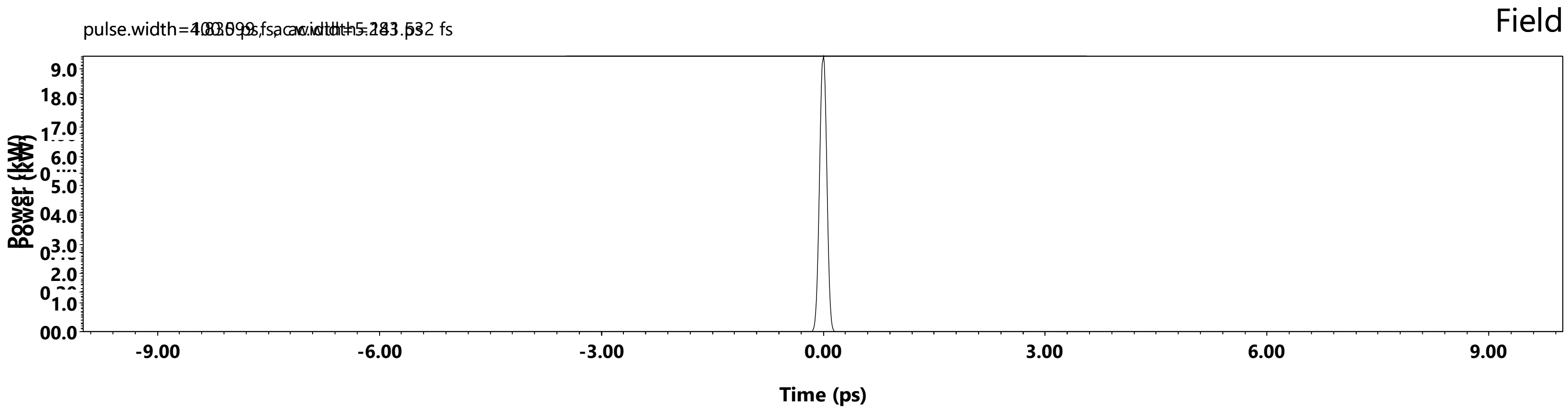
Create Pulse:

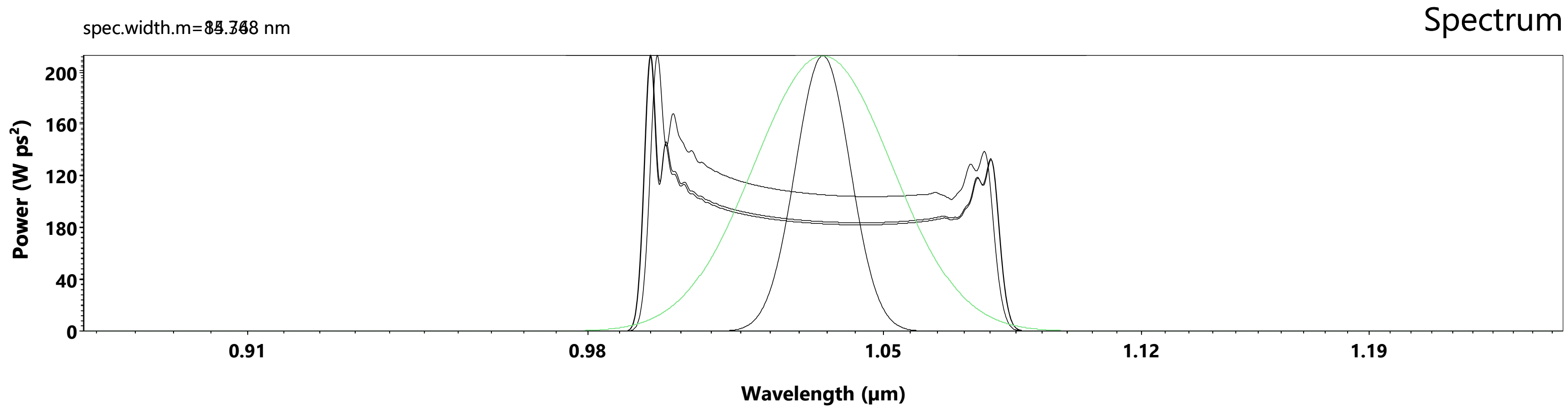




Multi-Element Propagation: Mamyshev Oscillator

After some roundtrips, we see the pulse converging. However, after many roundtrips, the pulse might destabilize.





Lecture 5

Multi-Element Propagation

Part 1:

Short Pulse Fiber Laser

Part 2:

Mamyshev Oscillator

Part 3:

Micro Comb Generator

Multi-Element Propagation: Micro Comb Generator

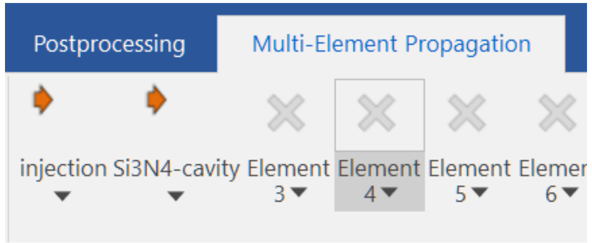
Alessia Pasquazi, Marco Peccianti, Luca Razzari, David J. Moss, Stéphane Coen, Miro Erkintalo, Yanne K. Chembo, Tobias Hansson, Stefan Wabnitz, Pascal Del'Haye, Xiaoxiao Xue, Andrew M. Weiner, Roberto Morandotti, Micro-combs: A novel generation of optical sources, Physics Reports, Volume 729, 2018, Pages 1-81.

Fiberdesk's multi element propagation can be used to simulate roundtrips in the micro-resonator. Please see section 5.1 of the reference for details. In principle, the first element simulates the in/outcoupling (boundary conditions) and the second element is the nonlinear propagation within the resonator.

$$E^{(m+1)}(0,\tau) = \sqrt{\theta}\,E_{\mathrm{in}} + \sqrt{1-\theta}\,E^{(m)}(L,\tau)e^{i\phi_0},$$

$$\frac{\partial E(z,\tau)}{\partial z} = -\frac{\alpha_{\mathrm{i}}}{2}E + i\sum_{k\geq 2}\frac{\beta_k}{k!}\left(i\frac{\partial}{\partial\tau}\right)^k E + i\gamma|E|^2E$$

So, only two elements need to be defined:

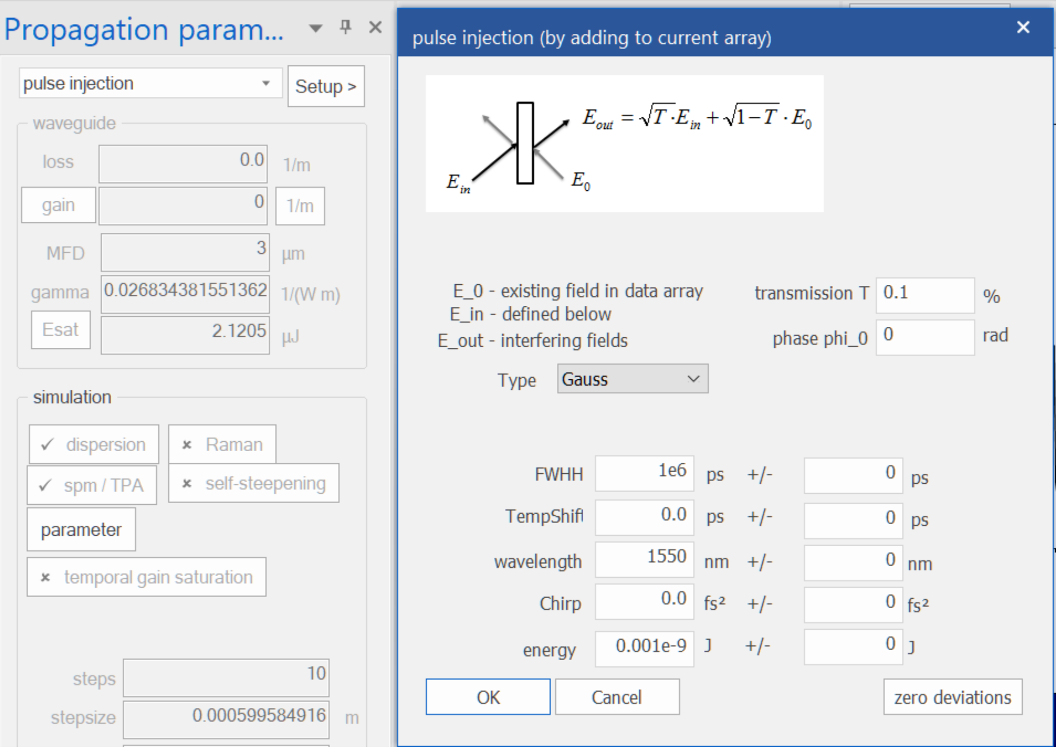


Please also note that the average propagation equation (LLE) can be used for simulating Micro Comb Generation but are intended for another tutorial.

Multi-Element Propagation: Micro Comb Generator

The injection element is done using the “pulse injection” propagation. As you can see, in the setup a low transmission (High Q Cavity) and long pulse duration (to simulate a cw injection) is given.

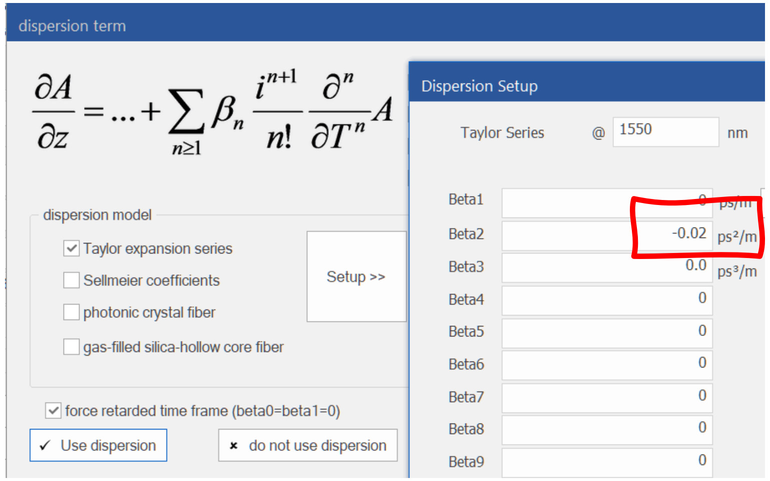
Save as injection.ppf

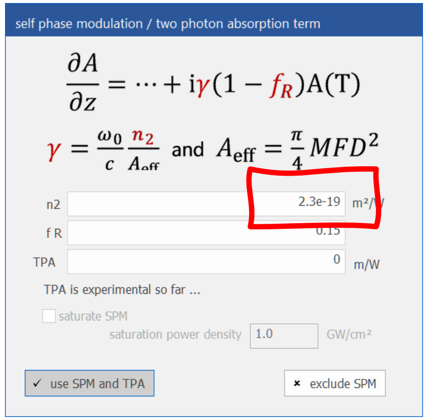


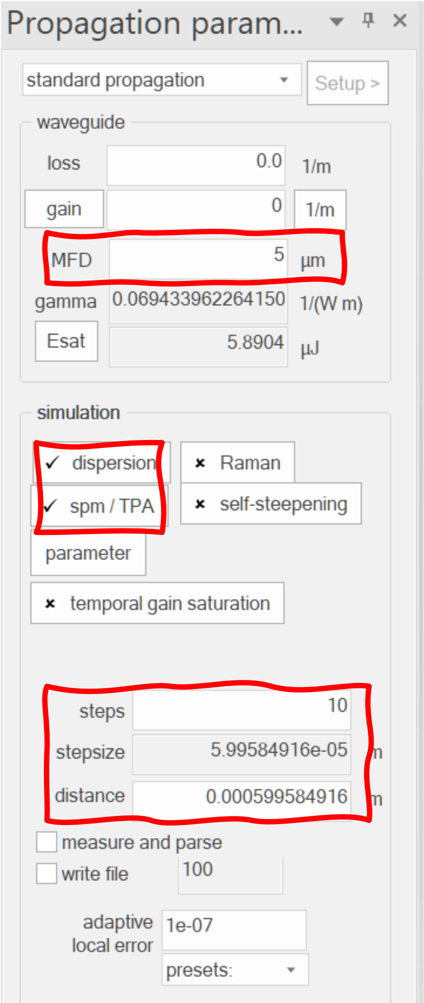
Multi-Element Propagation: Micro Comb Generator

The ring itself is defined as a standard propagation with the dispersion of the material (including the waveguide dispersion), the nonlinearity and length.
The dispersion is a simple second order approx. only.

Save as Si3N4-cavity.ppf







Multi-Element Propagation: Micro Comb Generator

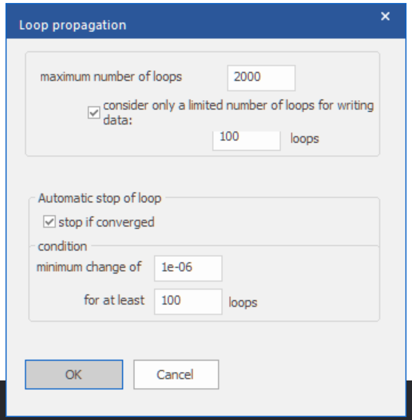
Starting the multi-element propagation. (Please make sure to have done the first steps of this tutorial to learn multi-element propagation.)

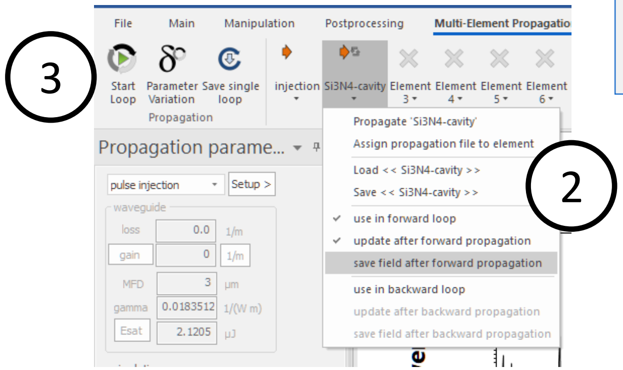
Quick reminder:

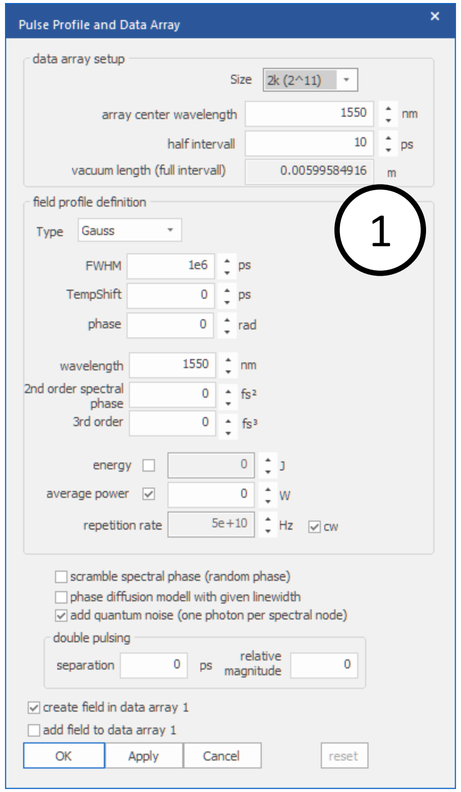
(1) Setup a field with a temporal window fixed to the length of the cavity (here ~60µm). This allows to draw a roundtrip map later on. We also only use quantum noise as the input come from the injected field.

(2) Assign the two propagations files to elements and use both in forward loop direction. Also, to see the chance after the propagation, switch on “update after forward propagation” of the second element. You might also save the field after forward propagation, in order to postprocess it later on, e.g. plot te graph on the next slide.

(3) Setup and start the loop.







Multi-Element Propagation: Micro Comb Generator

Using the python script, you can draw the save file and get this roundtrip map. It shows the built-up of structures from the cw input. The parameters now need to be refined to enable the desired output.