

Resonators study

Instructions for the practicum

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Information

- The practicum is two days long and usually takes place on Mondays and Tuesdays from 9:30 and 11:30 as well as 12:30 and about 16:00.
- The minutes must be submitted no later than two weeks after the test has been carried out.
- Please indicate the person taking the minutes in your minutes.
- A printed version of the instructions is available in the laboratory.
- Further information can be found at www.linac-world.de

Introduction: Accelerator structures

The history of particle accelerators began over 100 years ago. To this day, accelerator technology is being further developed and new accelerator structures are being constructed. The accelerator types are as extensive as their fields of application. The largest accelerators can be found in basic research, such as nuclear and particle physics. Prominent examples of this are the accelerators at CERN or GSI.

Beyond research, particle accelerators are finding more and more areas of application. For example, linear accelerators are used in medicine for radiation therapies. Other applications of particle accelerators include the sterilization of tools or the irradiation of food for preservation.

The first implementation of a high-frequency accelerator was carried out by the Norwegian physicist Rolf Wideröe. He constructed a series of cylindrical cavity electrodes

(so-called drift tubes), which were alternately charged differently (see fig. 1 and 2). One property of this structure was that, due to the polarity of the electric field, a particle beam could only be accelerated in every second acceleration gap, as can be seen in the schematic sketch 2.

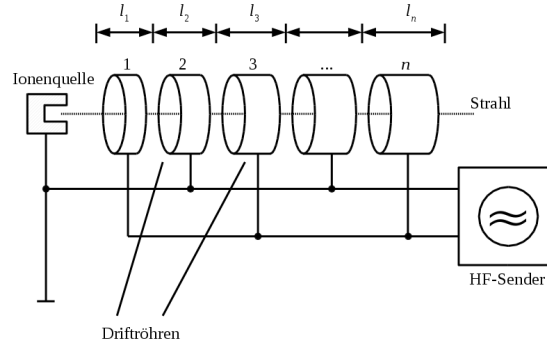


Figure 1: Representation of a Wideröe structure

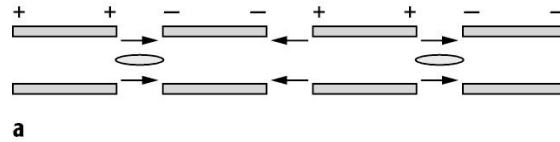


Figure 2: Plan view of a Wideröe structure

Luis Alvarez pursued a different approach shortly after the end of the Second World War with the accelerator architecture named after him. In this Alvarez structure, a transverse magnetic mode (TM mode for short) is excited in such a way that the opposite ends of the drift tubes are charged differently (see Fig. 2). Thus, a particle bunch can be accelerated in each gap. A schematic sketch of the Alvarez structure can be seen in Figure 3.



Figure 3: Schematic representation of an Alvarez structure

Both Wideröe structure and Alvarez structure can be assigned to the superclass of the so-called Drift Tube Linacs (DTLs). Although these DTLs can achieve high energies (with Alvarez accelerators, for example, a particle velocity of about $v \approx 0.6c$ can be achieved), however, the particle beam accelerated in them is increasingly transversely defocused, because the beam has an electrical charge, i.e. it undergoes a stronger deflection due to the Lorentz force

$$\vec{F} = q (\vec{v} \times \vec{B}) \quad (1)$$

This is compensated by magnets, e.g. quadrupole lenses. Another structure to be investigated in this experiment is the so-called radiofrequency quadrupole (RFQ). The RFQ consists of four long electrodes that run parallel to the beam axis. The RFQ is an accelerator structure that is especially suitable for lower velocities (about 0.01 to 0.06 times the speed of light). This makes the RFQ unsuitable for electron beams, as they usually penetrate the accelerator at 0.5 times the speed of light due to their low mass. Therefore the RFQ is all the more suitable for the initial acceleration of high-energy ion beams, because they enter the accelerator at a low speed.

Another feature that makes the RFQ a relevant accelerator structure is its design. The electrodes are not smooth, but have a sinusoidal structure. This structure allows the RFQ to achieve both transverse and longitudinal focusing in addition to acceleration, which counteracts defocusing by the Lorentz force. In this way, particle groups (*bunches*) necessary for later use can be formed more effectively from a continuous beam.

Motivation

In order to be able to accelerate particles on longer paths, larger experimental set-ups are also necessary. It should be noted that the maximum energy window of a resonator structure is non-linearly related to the length of the resonator. Since at a certain point it is no longer practicable to construct an ever longer continuous resonator for higher energies, several smaller resonators have to be coupled together. These can also support each other in their individual weak points. While an RFQ, for example, is able to focus a particle beam well transversally, to form it longitudinally to individual *bunches* and to accelerate it at the same time, this only works effectively at low energies. For higher energies, drift tube accelerators (DTLs) are the means of choice. A coupling of these two structures would now take over properties of both resonators, whereby first a simulation of the coupled system can determine which property prevails. Such a simulation is possible, for example, with the computer program CST Microwave Studio, which is also used in this experiment.

Instead of two high-frequency generators, both resonators are operated with a single high-frequency generator. This results in a saving of space and money.

The aim of this experiment is therefore to familiarize oneself with the given resonator structures, to examine their individual characteristics, such as their resonant frequency, and then to analyze changes and dependencies in the coupled system.

Structure

The practical measurements are performed on a 1:2 model of the RFQ-IH structure of the FRANZ project (read more: <https://link.springer.com/article/10.1140/epjp/i2016-16124-5>). It is a model designed for experiments to plan and tune the coupling of two different resonators. Unlike in FRANZ project, however, an RFD resonator is used instead of an RFQ resonator. The **D** stands for **D**ipol. This modification was made because in the dipole field the electric field in the center is not equal to zero, which is not guaranteed in the quadrupole field. This allows a comparison of the fields of the two

structures by means of interference body measurement along the imaginary beam axis. Tuning plates can be placed between the electrode supports of the RFD. These change the boundary conditions linked to the propagation of the electromagnetic waves and thus change the possible oscillation modes. The higher the tuning plates are installed, the higher the resonance frequency becomes.

In this experiment, a **Interdigitale-H** mode DTL structure (short IH-DTL) is coupled to the RFD structure. A more detailed description of this structure can be found in the bachelor thesis of the supervisor Malte Schwarz under the link <http://d-nb.info/1065726325/34>. The resonance frequency of the IH-DTL can also be varied via two tuners (one on the lid, one on the side wall of the tank). Figure 4 shows the resonators used in this experiment.



Figure 4: Left: View of the RFD along the beam axis, right: Plan view of the IH-DTL

Theory

Please familiarize yourself with the following topics for careful test preparation

- Cavity and line resonators
- Resonator quality and the 3 dB method
- S-Parameter
- Bead-pull measurement
- Coupling of electromagnetic waves in resonators

The following text should be used:

- Malte Schwarz: "Hochfrequenzabstimmung und Feldoptimierung des gekoppelten 1:2 RFD-IH-Modells für FRANZ", Bachelorarbeit
Available under the following link: <http://d-nb.info/1065726325/34>

But also the instructions of the IAP for the experiments *Störkörpermessung*, *Simulation und Messung an Resonatoren*, *Netzwerkanalysator (Interference body measurement, Simulation and measurement of resonators, Network analyzer)* can be consulted.

Tasks: Day 1

At the computer

Observe *Notes on CST MICROWAVE STUDIO*

RFD

1. Simulate the resonance frequencies for the model of the RFD at different tuning plate heights h (0 – 40 mm) using the eigenmodesolver. For automation, use the *Parameter Sweep* function with increments of 10 mm.
2. Simulate the resonance frequencies and E-field distribution along the beam axis for the model of the RFD at different tuning plate heights (0 – 40 mm) of **one end plate** while other tuning plates heights remain constant ($h = 5$ mm) using the eigenmodesolver. For automation, enter a new parameter in the Parameter list for the height of one end plate and use the *Parameter Sweep* function with increments of 5 mm.
3. How does the E-field distribution change with the change of the one end plate height? What height of the end plate gives the flattest E-field distribution?

IH-DTL

1. Simulate the resonance frequencies of the IH-DTL for different tuner insertion depths $ih_t1_einschubtiefe$ using the eigenmodesolver (0–100 mm). For automation, use the *Parameter Sweep* function with increments of 10 mm.
2. On the *Home* tab click on the *Mesh View*. What are the regions with the highest mesh density? How many tetrahedron elements are there in the current mesh?
3. Make a *Parameter Sweep* with 2 parameters: $ih_t1_einschubtiefe$ (*Linear sweep* 0 – 100 mm, increments of 10 mm) and $CellsPerMaxEdge$ (*Arbitrary Points*: 42, 50, 58, 63, 68). This sweep on $CellsPerMaxEdge$ parameter should roughly correspond to 100 000 - 300 000 meshcells with increment of 50 000. As it is time consuming consider starting this sweep at the end of the Day 1 to get the results by Day 2.
4. What tuner immersion depth is necessary to tune structure to 345 MHz resonance frequency? How much does the resonant frequency differ when tuner is fully pulled out ($ih_t1_einschubtiefe=0$) for $CellsPerMaxEdge=58$ case and for $CellsPerMaxEdge=68$ case?

In the laboratory

Observe *Notes on the Network Analyzer* and start the measurement at the IH-DTL. Display the results of the measurement and display them graphically. A USB stick is available in the laboratory for storing the results.

Measurement at the IH-Drift Tube Accelerator Model (IH-DTL)

1. Measure the resonance frequencies of the IH-DTL at different tuner immersion depths (from 0 cm in steps of 2 cm). The immersion depth of the IH-DTL starts at the highest possible position of the tuner. For easier tuning, notches are visible on the tuner at 1 cm intervals.
2. Measure the quality factor Q of the uncoupled IH-DTL at a resonant frequency of 345 (± 0.2) MHz using the network analyzer. Compare the order of magnitude of the measured quality with the simulated value, how can deviations be explained?
3. Perform a bead-pull measurement observing the *Instructions for performing a bead-pull measurement*.

Measurement on the Radio Frequency Dipole Model (RFD)

1. Use the network analyzer to measure the lowest resonant frequency of the RFD near 350 MHz and the resonant spectrum up to 1 GHz. Be careful not to move the tuning plates in the RFD.
2. Change the height of the end plate using wooden bricks for precise positioning (0, 1, 2, 3 cm). Perform a bead-pull measurement observing the *Instructions for performing a bead-pull measurement*.

Now compare the simulated results with the measured results. Are there deviations? If so, how can they be explained?

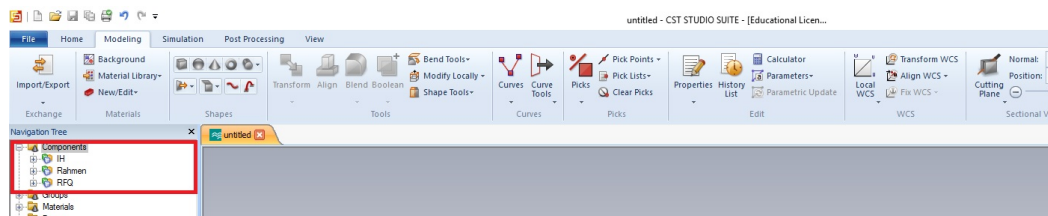
Tasks: Day 2

At the computer (coupled model)

1. Complete the coupled model in CST MICROWAVE STUDIO. Parts to add are specified in detail in *Notes on CST MICROWAVE STUDIO*.
2. Simulate the resonance frequencies and field distributions of the **coupled** RFD-IH model at different tuning plate heights and tuner immersion depths. Here, make the setup when both structures have the same resonant frequency (± 0.1 MHz), taking into account the results of the previous simulations. The simulation of the coupled system takes about 20-30 minutes, depending on the mesh accuracy.
3. Does the resonant frequency change after coupling?

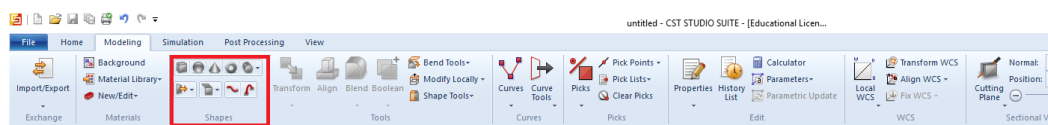
Notes on CST MICROWAVE STUDIO

1. Open the program using the shortcut on the desktop. A license message will appear when starting the program, which must be confirmed with a click on " I Accept".
2. In the folder Source Files you will find the files *Linac IH-DTL.cst* and *Linac RFD.cst* for the simulation of the uncoupled resonators, as well as the file *Linac RFD-IH.cst* for the coupled case. Create a new folder in the folder *Internship* with the naming scheme *YearMonthDayNames ofInterns* (example: 20190930 Thorsten-Klaus) and copy the files into this folder.
3. Open the file *Linac IH-DTL.cst*, *Linac RFD.cst* or *Linac RFD-IH.cst* depending on the task. In the latter case, you have an almost complete model of the coupled RFD-IH structure. You can change the view with the number keys and get a sectional view of the model with the **x**-, **y**- and **z** keys. The individual components are listed in the *Navigation Tree* under *Components*.

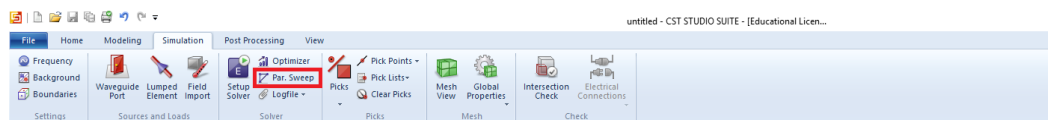


In order to navigate better within the 3D view of the simulated models, the following keyboard shortcuts are helpful:

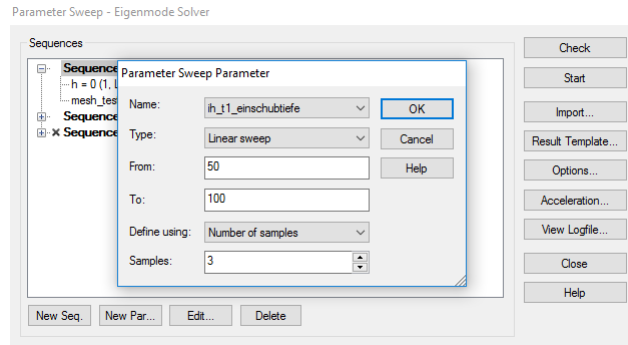
- **number pad** Rotates the model for viewing from different perspectives
- **Shift+C** switches the section view on/off
- **space** Reset position and zoom level of model view
- **mouse control wheel** Zoom in/out
- **Shift+left mouse button** rotates the model for viewing along an axis
- **STRG+left mouse button** rotates the model around all 3 dimensions without gaps



4. To simulate different values of a particular parameter, you do not have to simulate each value separately. The *Simulation* tab contains the function of the *Parameter Sweep*.



In the dialog screen you can set up a simulation series for a previously defined parameter under *New Parameter* by specifying the desired start and end value as well as the number and width of the steps. To start the simulation(s) click on *Start*.



5. After the mesh is completed (*Home* -> *Mesh View* -> *Update*) the number of tetrahedrons can be found in the right bottom corner of the window or in the graphics area in the left bottom corner under **High Frequency Mesh**.
6. To make a *Parameter sweep* on the mesh size: on the *Home* tab in the *Mesh* section click on the **picture** *Global Properties*. In the dialog window in the field *Cells per max model box edge - Model* enter a new parameter *CellsPerMaxEdge* and in the field *Cells per max model box edge - Background* type *CellsPerMaxEdge/2*, press *Enter*. In the new window set its *Value* to 40, press *OK*. Now in the *Parameter list* you can see that a new parameter is automatically added, which you can use later in the *Parameter sweep*.
7. The simulated E-field distribution along the beam axis can be found after completed calculation in the navigation tree on the left side of the program under **Tables** -> **1D Results**. The number of meshcells can be found after completed calculation in the navigation tree on the left side of the program under **Tables** -> **0D Results** -> **Get Number of Meshcells**
8. In task 2, i.e. in the coupled RFD-IH model, two components are to be added, a missing tuning plate in the RFD and the head piece of the IH tuner. To find out what they are, first take a close look at the model in the lab. The tuner can be found by opening the cover of the IH-DTL. Additionally you can compare the models of the uncoupled (*Linac IH-DTL.cst*, *Linac RFD.cst*) and the coupled model (*Linac RFD-IH.cst*).

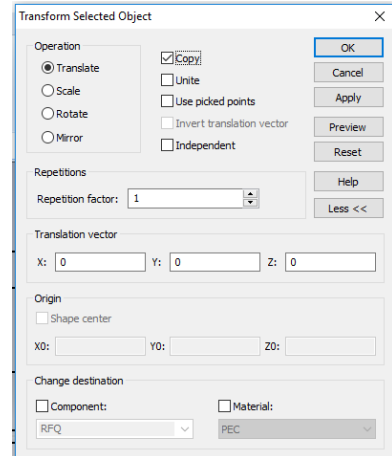
The missing tuning plate can be created by copying one of the existing ones:

- In the *Navigation Tree* under *Components* select one of the tuning plates (designation: RFQ-Txx) and open the Transform dialog via **Ctrl+T**.
- Check the box for *copy* so that the original disk is not simply moved. This creates a copy of the tuning plate, which is then moved by the specified coordinates. The dialog box can be seen in the figure below.

To find out the exact direction and amount of displacement, display the coordinates of two adjacent tuning plates. For this click in the *Navigation Tree* on **Components -> IH -> IH-Tuner -> right mouse button: Properties -> Define Brick**. The position of the tuner plates is given by a parameterization. Use this parameterization to create the missing tuner plate at the desired position. In case of uncertainties, you can have a preview of the placement of your tuning plate displayed at any time via *Preview*.

To create the box, go to the *Modelling* tab. There you will find various bodies that can be selected for modeling. Once you have selected a shape, **Esc** takes you to the dialog screen.

Here you can enter the desired coordinates of the box. The suitable coordinates of the box are obtained by adopting the coordinates of the existing simulation of the box of the uncoupled IH-DTL. To transfer the coordinates, first open the required file (*Linac IH-DTL**) and then go to **Components -> IH -> IH-Tuner -> right mouse button: Properties -> Define Brick**.



Now you can copy out the coordinates. However, you have to take care that the cylinder of the coupled model is rotated in comparison to the uncoupled model and that the cuboid has to be rotated as well. The rotation angle is taken from the other components of the IH-DTL, which have all been rotated by the same angle. Open the file *Linac RFD-IH.cst* and select a component like **Components -> IH -> IH-T1 -> Properties -> Transform Component (rotate)**, read the rotation angle and add it to the properties of the box. If you are unsure, you can get a preview here again via *Preview*. If you notice that despite the correct size and copied position of the box, it does not close flush with the tuner, but the box protrudes beyond it: make sure that the final position of the box must be variable depending on the tuner insertion depth - i.e. its position does not have a fixed assigned value, but via the tuner insertion depth (*ih_t1_einschubtiefe*) should be parameterized.

Note:

Export the E-field gradient of the sweeps (**Tables -> 1D Result beam axis e_1**), the quality (**0D Results -> Q-factor (Perturbation Mode)**) and the frequency gradient (**0D Results -> Frequency (Mode1)**) in order to be able to include these data in the protocol later. The export is done as follows: **PostProc -> ImpExp -> PlotData.ascii**. Export 2 different views of the model via **RegisterView -> Export Image**.

Notes to the Network Analyzer

A network analyzer is used in electronics, telecommunications and especially in high-frequency technology to measure the scattering parameters (S-parameters), i.e. reflection and transmission, of electrical measurement objects as a function of frequency. The network analyzer transmits a signal (incoming wave) from PORT 1 to the DUT (Device Under Test). The DUT reflects part of this signal. The rest runs into the DUT, is changed there (damped, amplified, phase-shifted) and appears at the output of the DUT as a transmitted signal. The transmitted signal returns to the network analyzer (NWA) via PORT 2. The reflection of the DUT is measured from the ratio of the reflected signal to the transmitted signal. The transmission is measured by the ratio of the transmitted signal to the transmitted signal.

In the following operating instructions, all operations beginning with "D-..." must be



Figure 5: Network analyzer after the bead-pull measurement on the coupled model pressed on the touchscreen of the display.

- The **Meas** key takes you to the menu where you can choose between the measurement parameters **S11** (Reflection from port 1 to port 1) and **S21** (transmission

from port 1 to port 2). The best way to measure the resonant frequency is to use the **S21** parameter.

- Setting the frequency range: The frequency range of the output signal (x-axis) can be set using the numeric keypad. To do this, first press the **Start** key and enter the start value. The size of the value can be defined with the keys **G, M, k, 1x** (according to the unit prefixes Giga, Mega, Kilo). Similarly, set the end value by pressing the **Stop** key.
- scaling of the display (y-axis) via **Scale -> D-Auto Scale**.
- Take a screenshot of the display and export it via **System -> D-Dump Screen Image**.
- Use the **Marker** key to set a marker. Use the numeric keypad and the order of magnitude keys to assign a position to the marker. The resonance frequencies can then be found via **Marker Search -> D-Peak -> Return**.
If you turn on **D-Tracking**, the marker remains at the maximum even if the corresponding frequency changes. By switching on the **D-Bandwidth** the NWA calculates the quality Q of the resonator by 3 dB method.

Instructions for performing a bead-pull measurement

WARNING: Please be careful not to damage the nylon thread that guides the debris. Make sure that the locking device under the table with the safety pin does not fall into one of the rollers on the table leg when you start the motor!

1. The bead-pull measurement is again measured with the **S21** parameter.
2. Make sure the Bandwidth is turned off under **Marker Search -> D-Bandwidth**.
3. Under **Sweep Setup**, go to **D-Points** and set the value to **1600**. (confirm via **x1**). This setting should remain the same until the end of the test.
4. Position the disturbance body in front of the input of the component to be measured. Set the speed of the motor to 2 before measuring.
5. Now the resonant frequency of the 0-mode must be found. To do this, go to **Scale -> D-Autoscale**, see the first conspicuous peak. To mark this, go to **Marker -> D-Marker1** and turn the knob until the marker is on the peak. To display only the peak of the basic mode, restrict the range by **Scale -> D-Autoscale -> Span -> 10 -> M/ μ Marker Search -> D-Peak D-Return -> D-Tracking -> ON**.

Alternatively you can set a marker with the option **D-Marker Search->D-Max** on the resonance mode and with the option **Marker Function->D-Center** the selected marker is set to the middle of the displayed frequency spectrum.

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6. Now enter the following settings to focus the NWA on the resonance mode and fix the measured quantity to the phase of the field:
Span -> 0 -> x1, Format -> D-Phase (To measure the phase difference between port 2 and port 1 ΔS_{21}).
 7. The network analyzer must still be calibrated (to set the phase difference to 0°) before each bead-pull measurement via
Cal -> D-Calibrate -> D-Response (Thru) -> D-Thru -> Wait for beep tone -> D-Done.
 8. Now set the duration of the recording of the NWA via **Sweep Setup -> D-Sweep Time -> Transmission time of the disturbance body t[s] -> x1**
 9. In order to perform the bead-pull measurement you must now press **Trigger -> D-Single** and start the motor of the disturbance body immediately (within 3 seconds). Then scale the display via **Scale -> D-Auto Scale**. After the measurement has been completed, stop the motor.
 10. smoothing (do not average! i.e. set Averaging to OFF!) you the curve with **Avg -> D-Smoothing -> ON -> Smoaperture -> 0,5 -> x1**
 11. To save the measurement files, you can use the USB stick supplied with the experiment. Press after the measurement to be saved:
Save/Recall -> D-Save Trace Data... or take a screenshot about **System->D-Dump Display Image**. To change the file name, press : **D-Input from the Front Panel**.
 Make sure to note which measurement data belongs to which tuner configuration.
 12. After the measurement, the trigger jumps to **D-Hold**, to perform a new measurement, it must be set back to **D-Single** or **D-Continuous**.

Evaluation of the bead-pull measurement

With your measurement data, you now receive the respective phase shift ϕ to the 1600 measurement points set previously

. When handling these values, you must observe the following:

- Convert the 1600 measuring points, which you get from the data of your graphs, into route sections. Use the previously measured velocity of the disturbance body as well as the measurement duration.
- It is possible that the coupled power is not sufficient to reproduce the course of the bead-pull measurement as shown in the figure 5 for the coupled model. If your results for the coupled model do not match the coupled measurement shown in Figure 5, consult your supervisor.

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- Note proportionality: $E(z) \propto \sqrt{|\tan \Delta\phi(z)|} \sim \sqrt{|\Delta\phi(z)|}$.

Photos of the practicum

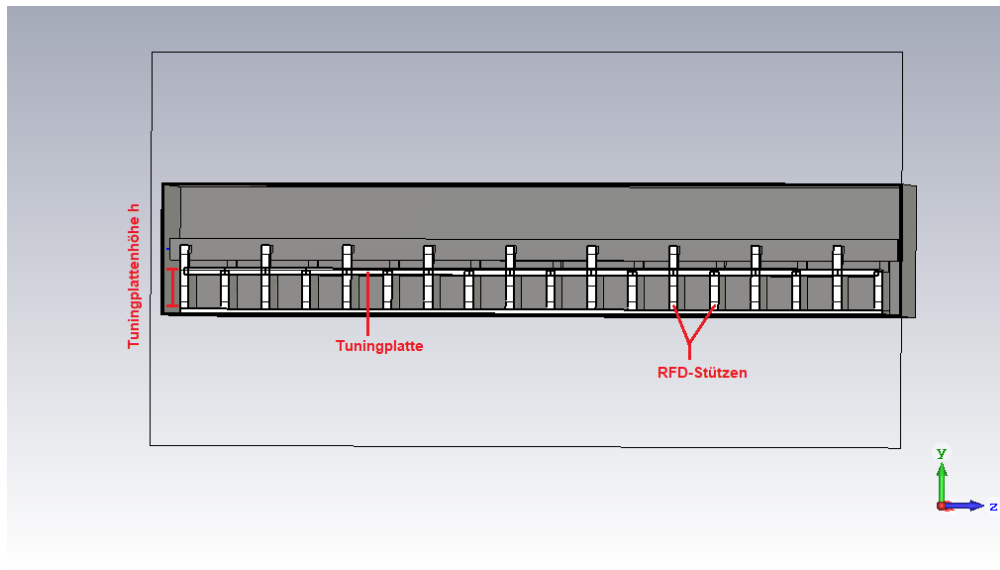


Figure 6: Simulation view of the RFD in x-axis direction

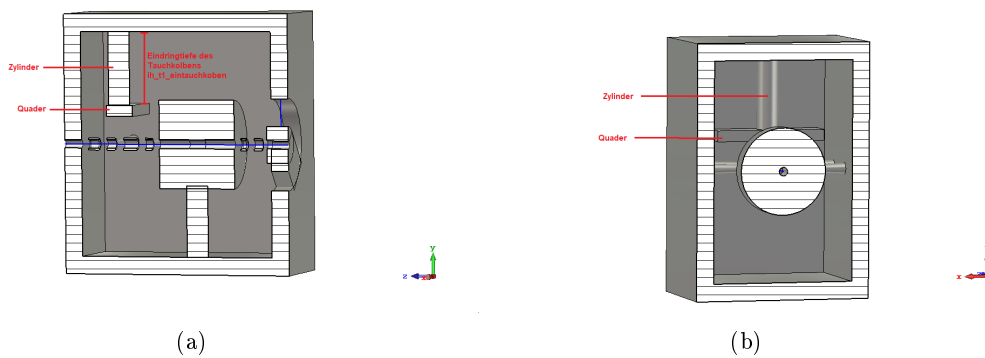


Figure 7: Simulation view of the IH-DTL from the side (a) and along the beam axis (b).