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KLYC. THE 1D/1.5D LARGE SIGNAL COMPUTER CODE FOR THE KLYSTRON SIMULATIONS. USER MANUAL. VERSION 6. INCLUDED *CGUN*. FOR THE 2D ELECTRON BEAM OPTICS SIMULATION

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Abstract

Almost all accurate and efficient 2D large-signal codes for klystron simulations are proprietary and are not freely available to the wider klystron community. The klystron code KlyC1D/1.5D has been developed at CERN recently, as an attempt to bridge the gap between the fast, but approximate 1D models and the time/resource consuming PIC codes. Here the notation 1D/1.5D is related to the fact that KlyC can choose between a 1D or 2D map of the electric field, while the particle motion is one-dimensional. KlyC is available in the public domain. This paper should help users to start with KlyC simulations. CGUN as a beam optics simulation tool is also included in this package, which allows users to simulate 2D optics problems in Klystrons and another linear beam devices.

Note, major updates comparing with version 5:

1) Small bugs fixed and improved performance and reliability
2) Uninterrupted graphical plot without stealing the focus
3) CGUN implemented into the package

Geneva, Switzerland
Date: 11/05/2022

Introduction

A number of computer codes for klystrons simulations have been developed in the past. These codes can be split into three categories depending on the complexity, completeness of the model and computational techniques being used. 1D codes like AJDisk [1], and KlypWin [2] operate in an idealized environment, where parameters of the RF cavities and space charge forces do not depend on the transverse position of an individual electron trajectory. 2D large-signal codes like TESLA [3], Klys2D [4] and FCI [5] account for all radial effects in the presence of an arbitrary solenoidal magnetic field. To economize on computation time, these codes use different approximations or external simulations of the electric field in RF cavities and drift tubes areas. Particle-In-Cell (PIC) codes like MAGIC2D/3D [6] and CST/3D [7] provide complete and self-consistent field solutions using fine discretization in space and time throughout the entire device. Unfortunately, the accurate and efficient 2D large-signal codes are proprietary and are not freely available to the wide klystron community. The klystron code KlyC1D/1.5D has been developed at CERN recently, as an attempt to bridge the gap between the fast, but approximate 1D models and the time/resource consuming PIC codes [8]. Here the notation 1D/1.5D is related to the fact that KlyC can choose between a 1D or 2D map of the electric field, whilst the particle motion is one-dimensional.

The KlyC computational algorithm is organized in such a way that the interaction between the electric field of the RF cavities, the space charge field and the longitudinal particles movement are self-consistent. During the first iteration, the electron beam will be modulated in the input cavity and propagate along the tube without taking the space charge forces and the RF cavities electric field into account. During the next iteration, the obtained longitudinal charge density modulation will generate initial distribution of the space charge field, excite the electric field in the cavities and the drift tubes, which in turn will affect the beam dynamics. Such a process will be repeated until the gap voltage in the output cavity has converged, providing a specified residual difference between the two last iterations.

In KlyC/1D charged particles are represented by disks. In KlyC/1.5D, a set of rings with different radii form the equivalent array of charged particles at the emission plane. The rings radial spacing is equidistant and each ring has an identical charge density, so that for the given beam radius, current in each ring will depend on the number of rings and its radial position. Through the propagation along the tube, each ring will preserve its radial position. The communication between the rings comes from the common RF field in the cavities and drifts to which they contribute individually.

CGUN is 2D optics code which is comprised of a magnetic module, an electro-static module and a beam trajectory module.

The magnetic module uses an integral method to analyze the B-field excitation relationship between blocks saving such information into a matrix. Combining with local magnetization information provided by the material properties, this problem can be solved with matrix mathematics and a finally self-consistent field distribution can be calculated.

The electro-static module is based on the Poisson equations solved both theoretically and using the Finite-difference method numerically. Such a classic process is quite similar to that used in the Eigen-mode module of KlyC.

The optics simulation is basically a combination of the Electro-static module and a trajectory simulation module. In each iteration of optics simulation, by adopting 4th Runge-Kutta method, trajectories of particles are calculated one by one from the emission point to the collision point on metal surface with the presence of static electric and magnetic field obtained from the modules mentioned above. The charge and current density in space will be statistically collected after all trajectories are traced, which will then be the used as the source information for EM simulations. Such iterations will be repeated over and over again until the solution reaches convergence, in which the final results are provided with a bunch of graphical plots. Instructions on CGUN will be demonstrated in the appendix of this manual.

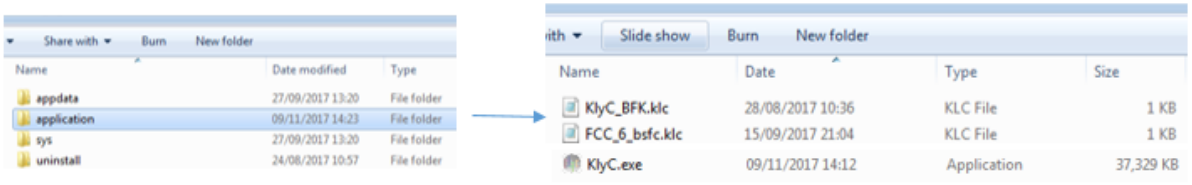
KlyC (KlyCv6.1) installation file and associated documentation are available at:
https://cernbox.cern.ch/index.php/s/vRO3EIR65HKeO4C?path=/Installtion%20and%20updates

The code for MACOS and WINDOWS, plus CGUN examples are all zipped into the file *KlyCv6_installer.zip*.
To receive the access to the code and installation instructions, please contact to the developers directly via emails: Jinchi.Cai@cern.ch ; Igor. Syratchev@cern.ch; g.burt1@lancaster.ac.uk

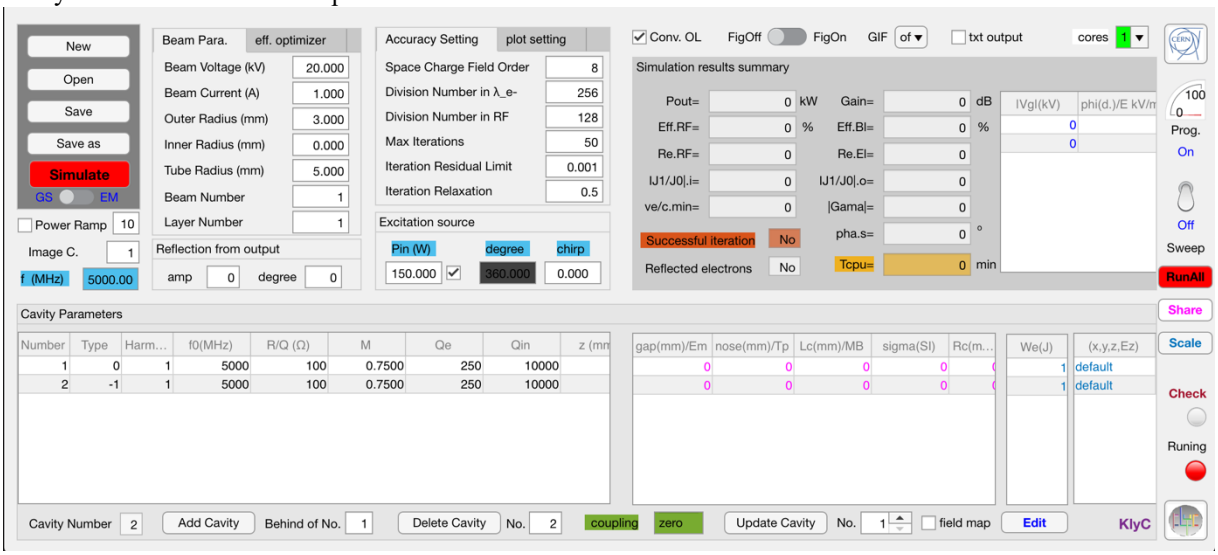
Chapters:

1. Getting started

After KlyC installation into the selected folder, open the folder. KlyC executable file is located in the 'application' folder. Double click on the file 'KlyC.exe' to start (You can also double click klc file to open KlyC by choosing the default program as 'KlyC.exe' in Windows):



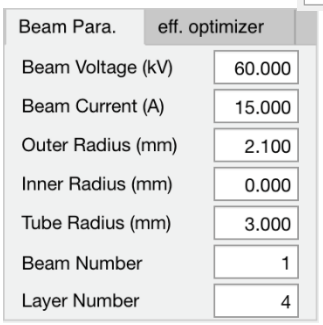
The KlyC GUI window will be opened:



As an illustration, we will use the 8 cavity, 1uP perveance, 0.4 MW Ku-band klystron. The tube has been designed, benchmarked with PIC CST/3D code and reported [9]. This example can be found in the example library with the name 'Kuband_5cavity_coupling_example_whole_forKlyCv5.klc', which can be downloaded from the same source as the KlyC installation file.

Using this tube as an example, the key steps to set up a KlyC simulation will be illustrated next.

First we need to specify the operating frequency: f (MHz) 17000.0 ; and the input power: Pin (W) 20.000 beam and drift tube parameters:

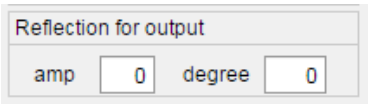


For full klystron simulations including the input cavity, the box located next to the value of the input power shall be checked. Unticking this box allows the user instead to start with a pre-bunched beam as will be discussed later. In the case of a hollow beam, the 'Inner Radius' of the beam shall be specified as well (0.0 by default for solid beams).

The KlyC particle emission algorithm is based on a model that uses emission from a metal surface (similar to the one used in the PIC CST/3D). In this case the beam kinetic energy will be fractionally converted into the DC potential of the beam space charge, commonly known as space charge depression. The amount of converted energy will depend on the beam power, perveance and the drift tube filling factor (space charge). To enable such an emission mechanism (recommended), the value of the 'Image C' shall be set to -1: Image C. -1 . If you wish to have a fixed beam energy with no space charge depression 'Image C' should be set to 0.

In 2D simulations, by default, the current density across the beam cross-section is constant. The user can introduce a radial variation of the beam current density as a linear function by specifying the chirp value: chirp 0.000 .In this case, we define the density chirp as $\alpha = \frac{J(r_{m2})-J(r_{m1})}{J_0} = \frac{J(r_{m2})-J(r_{m1})}{I_0/\pi/(r_{m2}^2-r_{m1}^2)}$;

The klystron can also be simulated with the option of specifying a mismatched RF load. In this case the normalized amplitude (voltage) and phase of the reflection shall be specified in:



KlyC supports multi-core processors (up to 4):  For 2D simulations this option allows an increase in the simulation speed by about 30% to 100%, depending on the specific case.

Upon completing the simulations, KlyC can generate convergence history, multiple graphics, and animations and extract the data into text file(s). All these can be enabled or disabled by using the corresponding buttons on a panel:

2. RF cavities and klystron layout.

The general cavity parameters and klystron layout can be introduced directly into a cavity parameters table:

Cavity Parameters

Number	Type	Harm…	f0(MHz)	R/Q (Ω)	M	Qe	Qin	z (mm)
1	0	1	16990	56.7592	0.3902	300	3.0355e+03	0
2	1	1	17110	60.8162	0.5338	4.6360e+05	3.0351e+03	19
3	1	1	17110	60.8162	0.5338	4.6358e+05	3.0351e+03	42
4	1	1	17100	60.8162	0.5338	4.6358e+05	3.0351e+03	65
5	1	1	17120	60.8162	0.5338	4.6358e+05	3.0351e+03	84
6	1	1	17060	56.7592	0.3902	4.6358e+05	3.0355e+03	106
7	1	1	17060	56.7592	0.3902	3.2618e+05	3.0355e+03	115
8	1	1	16545	34.5684	0.4120	1000000	2.2410e+03	122
9	1	1	16545	34.5684	0.4120	1000000	2.2410e+03	123.7000
10	1	1	16545	34.5684	0.4120	1000000	2.2410e+03	125.4000
11	-1	1	16545	34.5684	0.4120	116	2.2410e+03	127.1000

The cavities types are as follows: Type 0 is an input cavity, 1 is bunching cavities and -1 is an output cavity. The harmonic number of each cavity shall be specified in the third column, with 1 being a standard cavity at the beam drive frequency. The **frequency** (column 4), external **Q factor** (column 6) and **cavity position** (column 9) have to be defined by user for each cavity.

In the simulations, KlyC uses the 1D/2D maps of electric field in the drift tubes and cavity areas. KlyC suggests few options to generate these maps.

1. Gaussian approximation.

In this case the user has to specify directly each cavity's impedance (R/Q), beam coupling (M) and intrinsic Q factor (Qin). Impedance and beam coupling are defined as:

$$\rho = [\int_{-\infty}^{+\infty} \frac{|e_z^*(z)|}{\sqrt{\omega_0 \varepsilon_0}} dz]^2, |M| = |\frac{\int_{-\infty}^{+\infty} e^{-j\omega_0/v_{e0} z} e_z^*(z) dz}{\int_{-\infty}^{+\infty} |e_z^*(z)| dz}|$$

Following, the longitudinal distribution of the normalized electric field will be reconstructed:

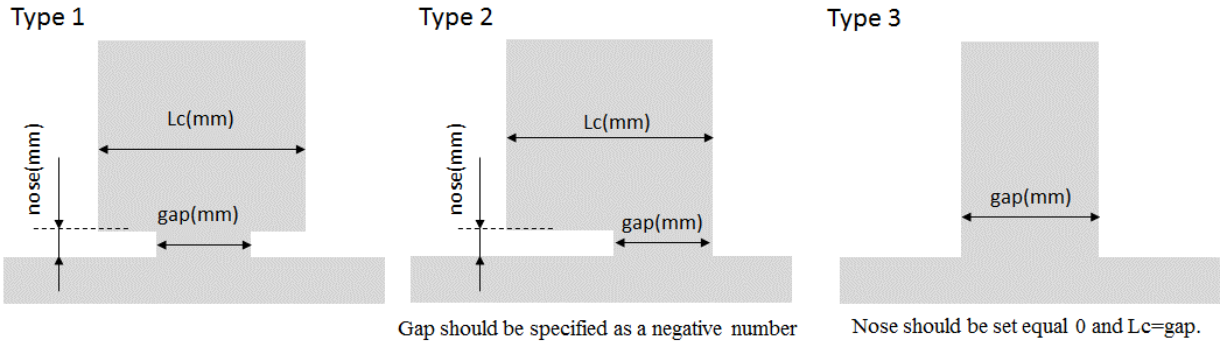
$$e_z^*(z) = k\sqrt{\frac{\rho k_0}{\pi \eta_0}} e^{-k^2 z^2}, k = \frac{1}{2} \frac{\omega_0/v_{e0}}{\sqrt{-\ln|M(\omega_0/v_{e0})|}}$$

This electric field distribution holds only longitudinal variation and is constant across the beam tunnel. This option is similar to the one used in 1D computer code AJDisk.

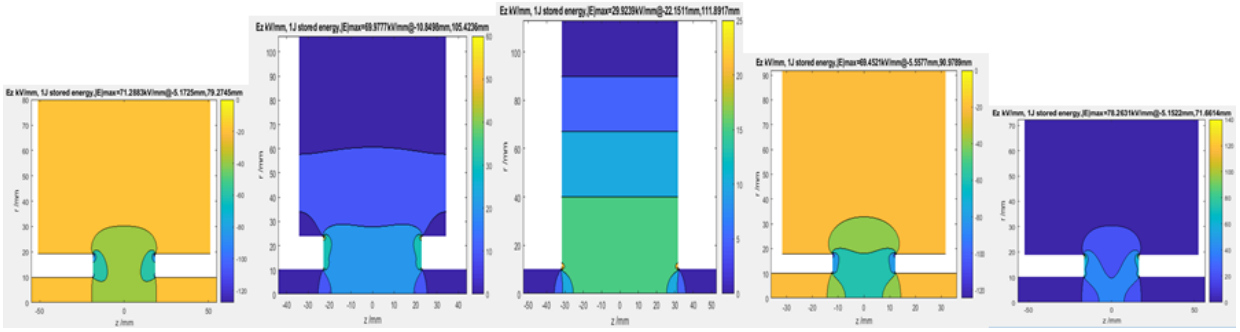
2. KlyC internal cavity calculator.

The specially developed eigenmode solver is integrated into the KlyC. To facilitate the very fast RF cavities parameters calculation, the KlyC cavity calculator supports three the most common topologies of RF cavities that are used in the klystrons, which are shown in the next figures. In the EM module window, for each cavity, the user has to define three geometrical parameters and specify the conductivity of the material being used:

gap(mm)/Em	nose(mm)/Tp	Lc(mm)/MB	sigma(SI)	Rc(m...
0	0	0	0	0
0	0	0	0	0



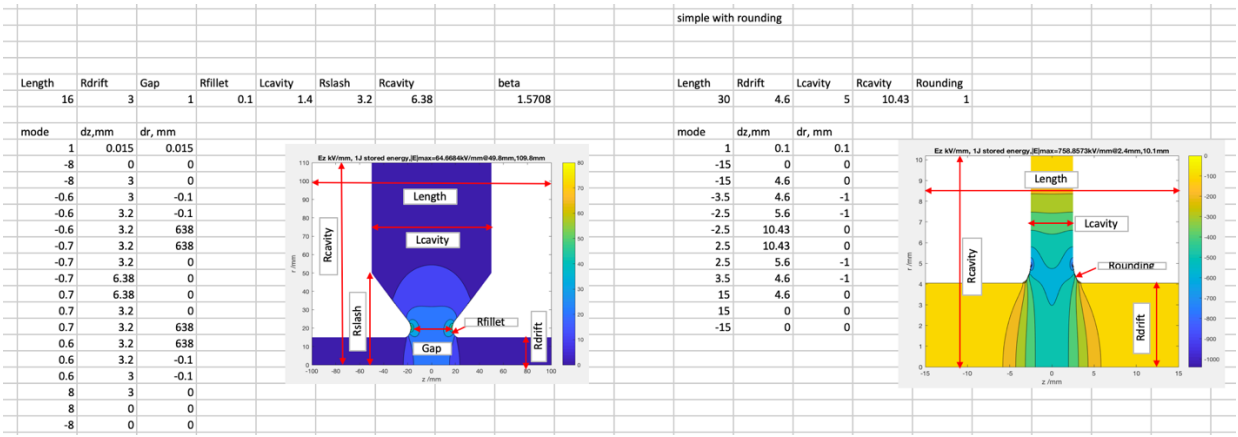
When the geometry of the given cavity is defined, click on Update Cavity No. 5 . KlyC will run eigenmode solver and adjust the cavity radius (Rc) to satisfy the cavity frequency specified in the cavity parameters table. It will calculate R/Q, beam coupling M and Qin. The calculated values will be automatically updated in the cavity parameters table. The values of R/Q and M are calculated as the ones averaged over the beam cross-section. If the field map box is checked: field map KlyC will generate the graphical information about the cavity. The Ez field maps in the 5 cavities simulated by KlyC cavity calculator:



In general, it is not necessary to update the cavities every time using 'update cavity' button. When the klystron simulation is started, KlyC will update all the cavities automatically. In all the cases, the cavity position with respect to the one defined in the cavity parameters table will correspond to the gap center. If the user made a topological mistake during cavity geometry specification, the 'check' indicator (bottom right on the GUI window) will blink yellow when the user update the cavity.

3. KlyC EM module.

This option allows user to generate the arbitrary cavity geometry using geometric primitives like lines and circular arcs. We may suggest the users to use Excel to generate parametric model. Here are 2 examples prepared in Excel:



Length	Rdrift	Gap	Rfillet	Lcavity	Rslash	Rcavity	beta
16	3	1	0.1	1.4	3.2	6.38	1.5708

mode	dz,mm	dr, mm
1	0.015	0.015
-8	0	0
-8	3	0
-0.6	3	-0.1
-0.6	3.2	-0.1
-0.6	3.2	638
-0.7	3.2	638
-0.7	3.2	0
-0.7	6.38	0
0.7	6.38	0
0.7	3.2	0
0.7	3.2	638
0.6	3.2	638
0.6	3.2	-0.1
0.6	3	-0.1
8	3	0
8	0	0
-8	0	0

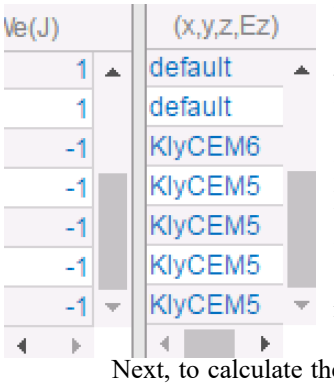
simple with rounding

Length	Rdrift	Lcavity	Rcavity	Rounding
30	4.6	5	10.43	1

mode	dz,mm	dr, mm
1	0.1	0.1
-15	0	0
-15	4.6	0
-3.5	4.6	-1
-2.5	5.6	-1
-2.5	10.43	0
2.5	10.43	0
2.5	5.6	-1
3.5	4.6	-1
15	4.6	0
15	0	0
-15	0	0

The columns with numbers in this examples contain the geometry information to be saved separately in the dedicated text file. Here, in the first line, number of the mode of interest, in order of eigen frequency, is specified in the first column; mesh discretization length for z and r directions are depicted in the second and third column

The geometry should start with min/negative (z) and min(r) position. From this point, geometry characteristic points description in clockwise direction shall be written line by line. Z and R coordinates should be put at the first and second column in a line. The intersection points for a straight line (vertical or horizontal) should be followed by an indicator number '0'. The intersection points for an arc should be followed by an indicator number '+r' or '-r'. + means the arc is clockwise defined and – means the arc is anticlockwise defined and r is the radius of the arc. Note that the tilted line is defined as an arc with very large radius. The dimensions are in 'mm' by definition. After the geometry file is completed in any TEXT EDITOR or EXCEL, the file should be saved as a text file into the project working folder where the current klc file is located.

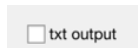


We(J)	(x,y,z,Ez)
1	default
1	default
-1	KlyCEM6
-1	KlyCEM5
-1	KlyCEM5
-1	KlyCEM5
-1	KlyCEM5

In the KlyC GUI window, in the (x,y,z,Ez) column, if the name is set as 'default', the 1D Gaussian E-field pattern will be generated (if GS is selected), or the 2D field map will be calculated using simplified cavity calculator (if EM is selected): 

. The value of the stored energy, We(J) in this case shall be set to 1, that corresponds to 1J stored energy.

In the case of the EM module (the GS/EM trigger shall be set to EM) is used for the E field 2D map calculation, We(J), shall be set to -1 and the name of the text file with geometry shall be written in the (x,y,z, Ez) column. The geometry text file can be opened and edited directly from GUI window. For that the user shall select the cavity number and click the 'Edit' button: 

. When the editing is done, the file shall be saved and CLOSED to enable KlyC to do the calculations. Next, to calculate the cavity parameters, user shall click on the 'Update cavity' button. With that option KlyC will generate the 2D field maps, calculate and write into the parameters table R/Q and M of the cavity. Also, in the column 'gap(mm)/Em' the calculated maximal surface field (MV/m) will be shown. R/Q and M values in the table will be calculated as an average value across beam cross-section. In this case the cavity frequency is taken from the parameter table and not from the dimensions given, such that the cavity dimensions do not have to be perfectly tuned when doing cavity frequency sweeps. The calculated cavity frequency will not be displayed. Instead the normalized frequency error with respect to the one specified by user in the input parameters table will be shown in the column R (cm). We recommend to make a few iterations of the cavity geometry editing the parameters to bring this error value to below 0.001. For the klystron simulation this error is not an issue, as KlyC will use the frequency specified in the parameters table by the user, but such tuning will ensure correct values of R/Q and M. If the 'field map' box is checked prior the 'Update Cavity' activation, KlyC will generate E and B fields 2D maps, the E(z) field distribution at the different radii and radial distributions of the R/Q and M within the beam area. If the 

was checked, KlyC will save E(z) distributions into the text files: KlyCcavityN.txt (N is a cavity number) . Throughout the klystron simulations, the calculations of the cavity parameters using the EM module will be done for every simulation. These calculations could take some time, especially if the mesh discretization is small. This process can be simplified, by importing the E(z) distributions generated by KlyC from previously simulating the cavity in the EM module (as explained above) or from other codes (as described below). In this case, after the cavity update is done, the name of the cavity geometry file shall be replaced

by the corresponding name of the E(z) filed file generated by KlyC and the value of We(J) shall be set to '0'.

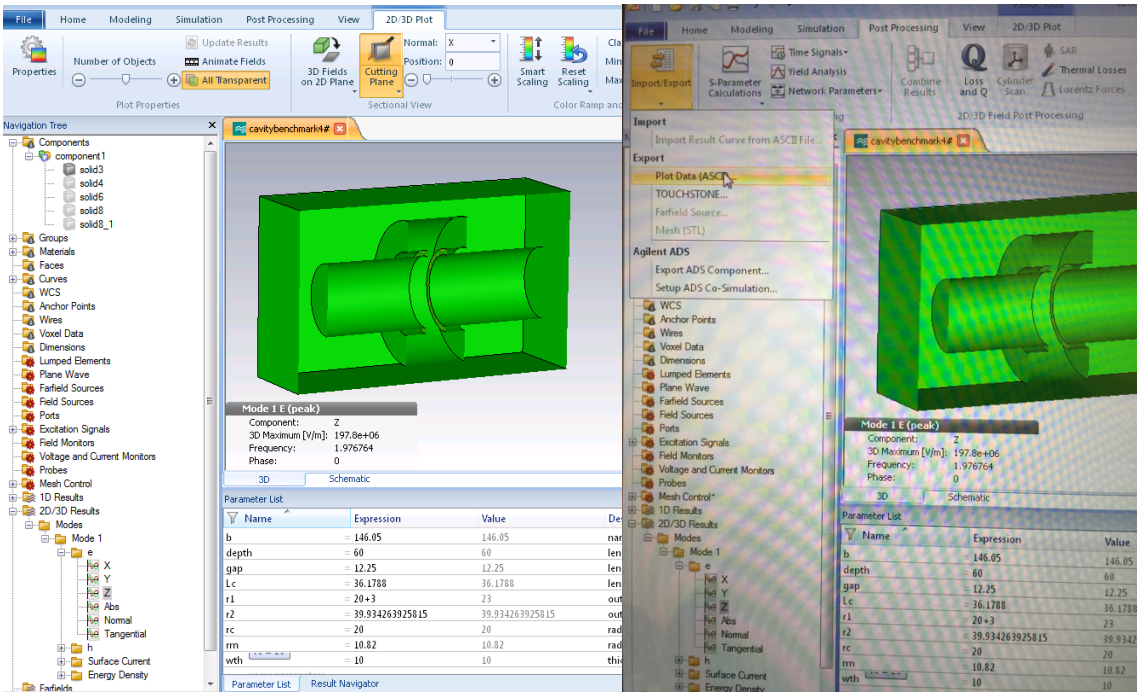
In case, if the cavities were not manually updated, the parameters calculations will be done automatically upon launching the klystron simulations. As a tip, we can recommend to benchmark the KlyC EM results with results of HFSS or CST eigen solver for one of the cavities being used. In this process, the user can manipulate with 'dr' and 'dz' mesh discretization values in the cavity geometry file (note: dr shall not be necessary equal to dz) and define to the best combination.

3. Field imported from other 3D codes

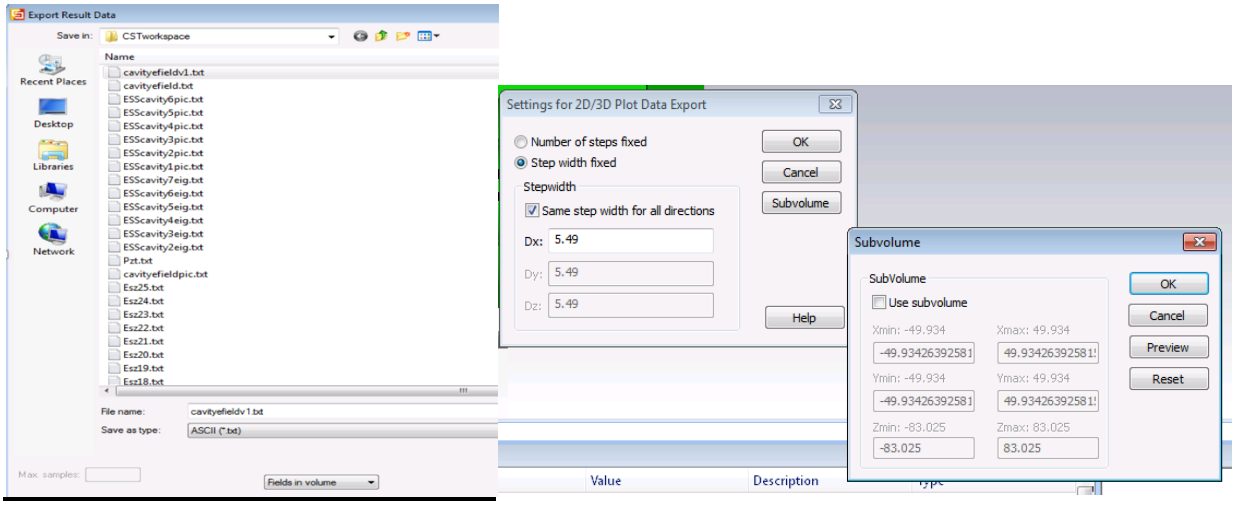
Here, CST MWS and HFSS will be used as examples. Similar data processing can be done with other 3D codes.

Preparing imported data from CST:

Important: Z direction should be longitudinal direction (along the beam direction) and the center of the cavity gap shall be set to (0,0,0). If MBK cavity, or the cavity with a special transverse shape are considered, then the transverse position of the cavity should be modified in a way that the beam axis of one of the individual beamlet shall be aligned with global Z axis.



1. After the eigen mode simulation is done, create the 3D plot of E field for the specified mode

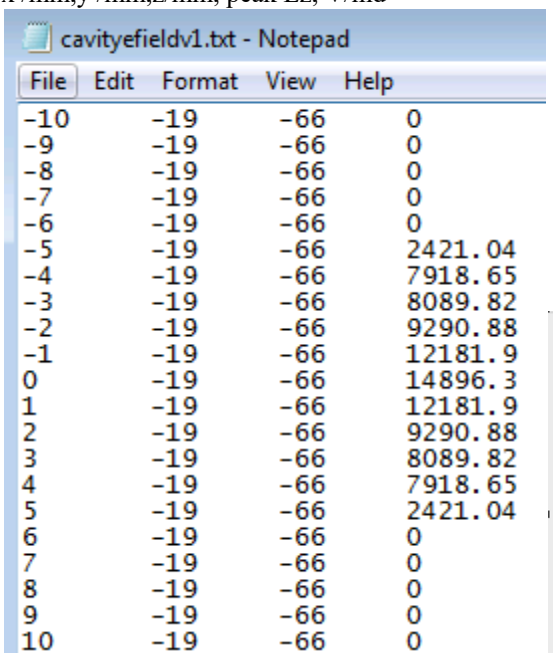


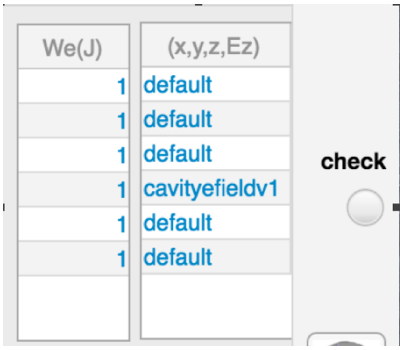
2. Choose the name to save the txt file. Choose the “Field in volume” at the bottom line.
3. Choose the region (cubic sub-volume) and output precision (plot mesh) before pressing OK.
4. Choose the name to save the txt file (cavityefieldv1 in this example).

x [mm]	y [mm]	z [mm]	ExRe [V/m]	EyRe [V/m]	EzRe [V/m]	ExIm [V/m]	EyIm [V/m]	EzIm [V/m]
-20	-20	-66	0	0	0	0	0	0
-19	-20	-66	0	0	0	0	0	0
-18	-20	-66	0	0	0	0	0	0
-17	-20	-66	0	0	0	0	0	0
-16	-20	-66	0	0	0	0	0	0
-15	-20	-66	0	0	0	0	0	0
-14	-20	-66	0	0	0	0	0	0
-13	-20	-66	0	0	0	0	0	0

KlyC data file shall be next constructed from the CST output data (shown above). The first 3 columns (x,y,z)/mm and column 6 (EZRE [V/m]) shall be preserved. The columns and the text header shall be removed. The edited file (one may use Excel for editing) will have the format as shown below. This file shall be saved into text file with the specified name (into the same folder where klc is located) and then can be used as an input file for KlyC. In the We(J) column, the actual value of the stored energy in the cavity for the imported field map has to be specified. In general, CST and HFSS assign the stored energy in eigen mode simulations to 1J. The user can introduce different data processing methods, but should obey the format of the data file shown below. Note, it is important that in every case, the full 3D cavity simulations are used, because KlyC is using 3D field map to select and create 2D field map.

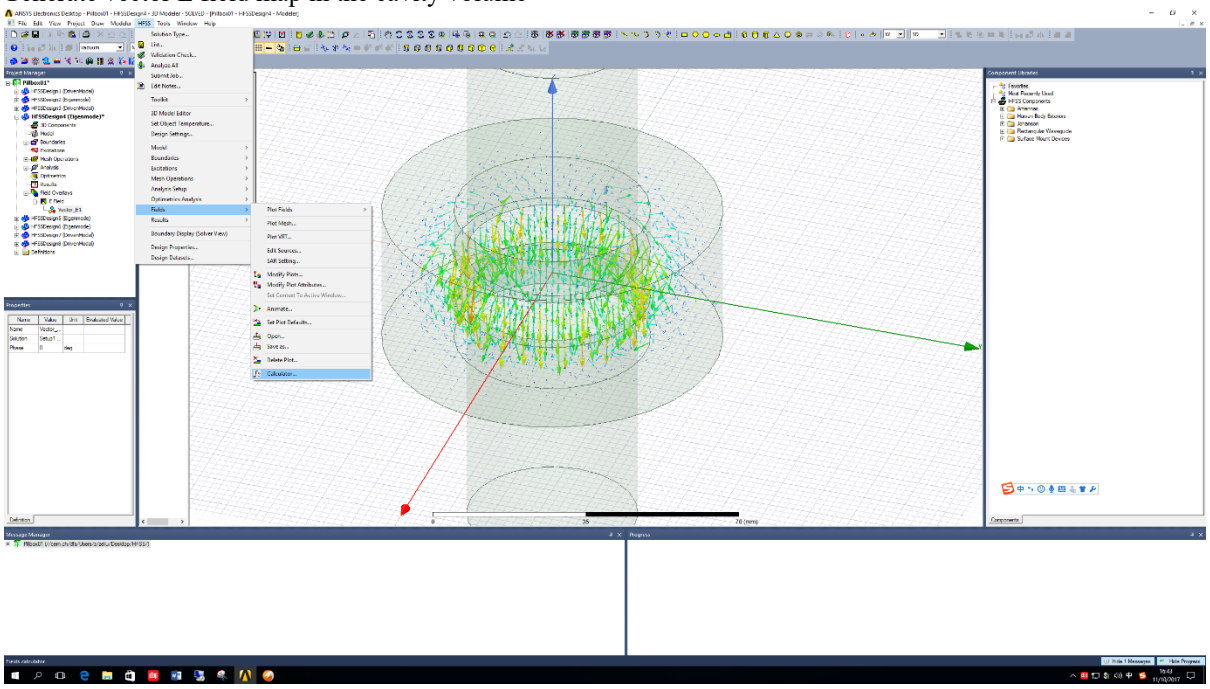
x /mm,y /mm,z/mm, peak Ez, V/md



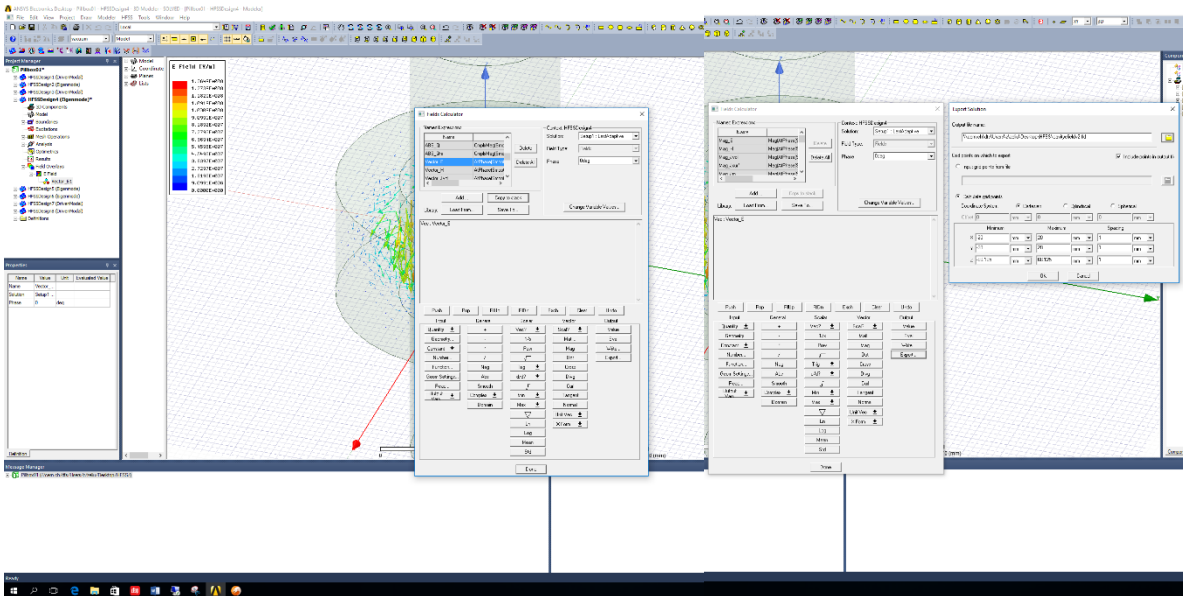


Preparing imported data from HFSS

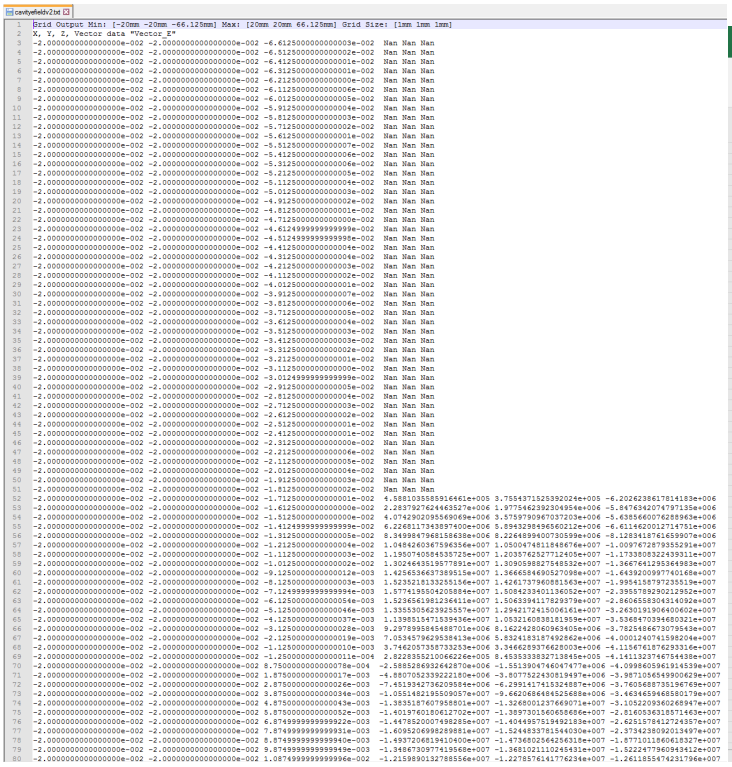
Generate vector E field map in the cavity volume



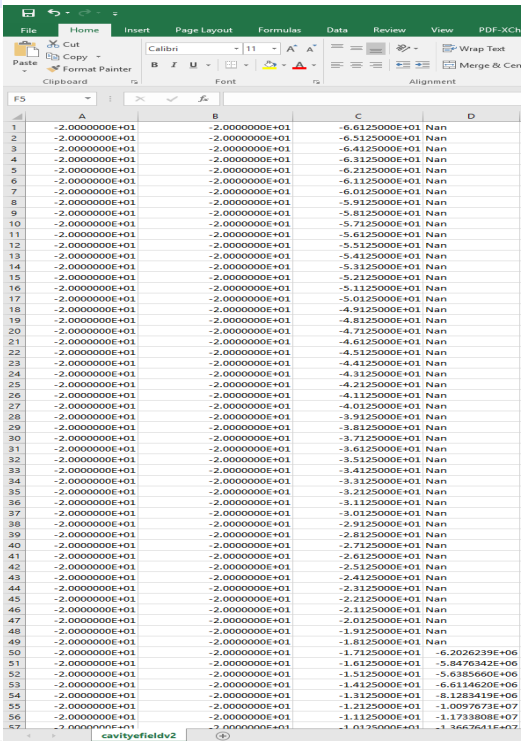
Choose the calculator in the post-processing sector.



Vector_E should be copied to stack before pressing Export button.
Export field data by selecting a specific cubic region and plot as above figure shows. Change the postfix of exported data file as .txt and open it:



Raw Data



Data processed

Notice that the coordinate dimensions are given m. So three steps are needed file ready for import into KlyC.

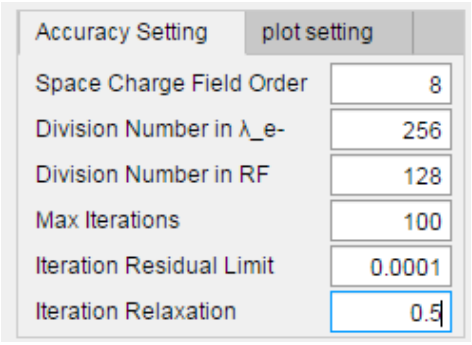
1) Delete the text head in the first 2 rows to make it a sheer datasheet.
2) Delete 4 and 5 columns, thus making Ez (V/m) as updated 4th line.
3) The data in the first 3 columns should be multiplied by 1000.

Save the file with default settings into the working project folder.

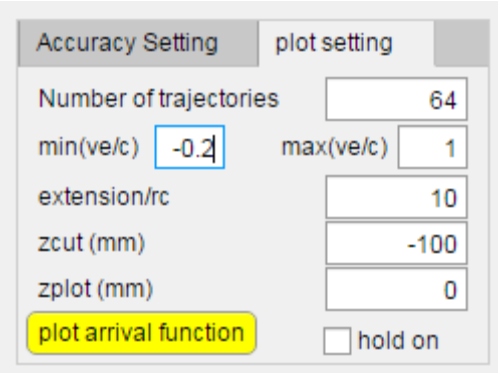
From our experience, this field import option is useful, if the special cavity shape (rectangular for example) or the MBK cavities are involved. In the cases with circularly symmetric objects, the KlyC EM module is very fast and accurate enough. If the imported 3D electric field map does not hold axial symmetry around the beam axis (like in MBK for example), KlyC will generate the 2D map with averaging of the azimuthal variation. Thus the user should consider the possible errors in the beam wave coupling simulations and try to minimize this effect through the cavity geometry optimization.

4. Model discretization (accuracy) settings & Plot settings.

In KlyC, the model discretization is controlled by selecting the number of spatial divisions per electronic wavelength (Nz), the number of emitted particles per RF period (Nt) and the number of harmonics to be used in calculations of the space charge field (Ns). Simulations will be completed when the requested iteration residual limit is reached or the number of iterations exceeds the specified limit. The residual limit is measured using the maximum convergence of the gap voltage in the all cavities to ensure a consistent convergence. The iterations convergence process can be optimized by adjusting the iteration relaxation parameter (0.5 by default). This parameter controls the weight which will be used by KlyC to account for the result of the given iteration when moving to the consequent one. For every case the relaxation parameter can be adjusted (normally <0.5) to minimize the number of iterations (simulation time) to reach the convergent criteria. The model accuracy settings which are recommended for the klystron optimization process are:



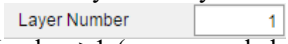
The output graphics and animations generated by KlyC can be controlled from the plot settings menu:

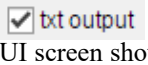


The 'Number of trajectories' specifies the number of trajectories in the Applegate diagram, it shall be less than 'Division Number in RF'. The velocities limits control the scale of the pictures and animations related to the bunched beam phase diagrams. The 'extension/rc' allows the specification of the length (normalized to drift tube radius) of the drift tube after the output cavity. By default, this parameter is set to 2, in order to minimize the simulation time. Parameter 'zcut' specifies the starting position of the plots which are functions of the longitudinal coordinate and also it serves as absorbing plane if there are reflected electrons. The applications of parameter 'zplot', 'plot arrival function' button and 'hold on' box are explained later in the text.

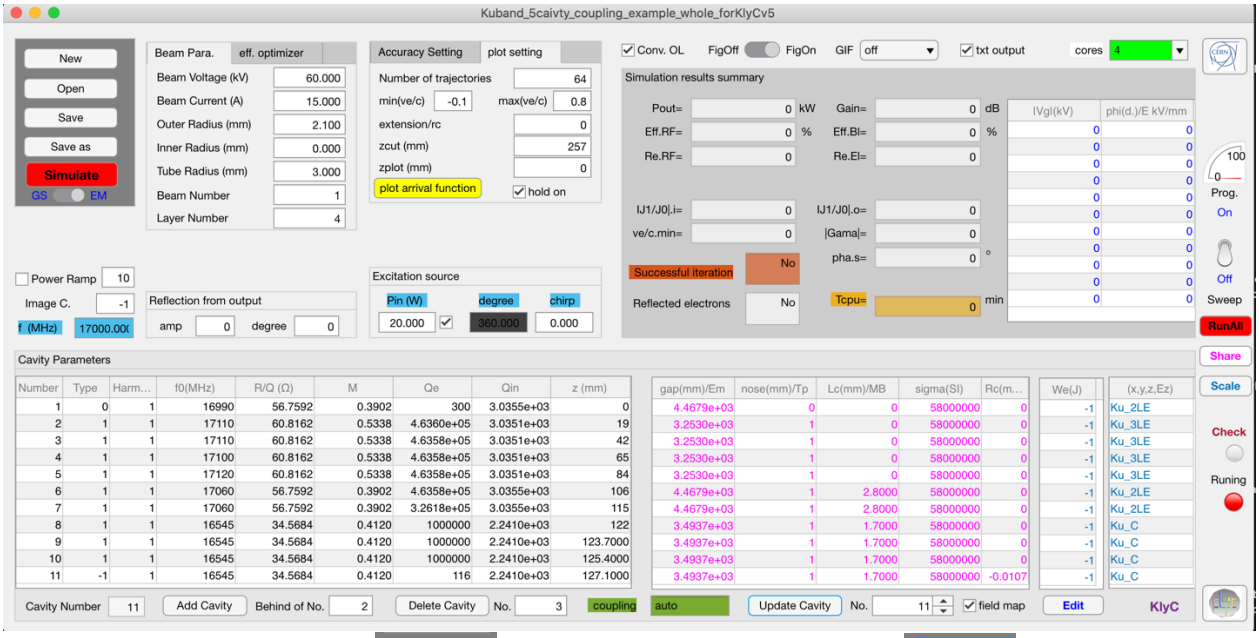
5. Starting simulations.

Before running the simulations, the user can select between two regimes using the 

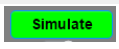
switch.
GS mode is recommended when the cavities parameters have been defined in the cavity parameters table. In this case, the 1D cavity field maps will be generated and used in simulations. **EM** mode shall be chosen if cavities are designed using the KlyC cavity calculator, or EM module, or when the electric field is imported from the other eigenmode solvers. In this case the 2D cavities field maps will be generated and used in simulations. Notice that a 2D field map could also be used in Gaussian module but there will be no radial dependency; and a 1D field map could be used in EM module as well in which case the averaged field profile will be used for every radial layers.
The user can choose between 1D and 2D simulations by specifying the 

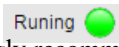
If Layer Number =1, the 1D simulations will be executed. If Layer Number >1 (recommended 4 at least), the 2D simulations will be done. If 2D option is chosen, the space charge simulations will be done in 2D, independently of the simulation regime GS/EM.
The results of the simulations will be saved into txt file if the box 

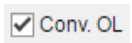
is checked.
When the project is fully prepared (see the next picture with KlyC GUI screen shot), it is recommended to save each project into a dedicated folder, where all the files generated by KlyC will be located after. When saved, the project_name.klc file will be created. Next time, the KlyC can be started by clicking on the existing *.klc file in the folder.



To start simulation, press on the 

button. The button will turn green 

as well as 'Running' indicator: 

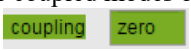
It is strongly recommended to check the convergence on line box: 

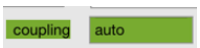
In this case the iterations progress window will pop up and will allow to monitor the simulation process. If it is need to terminate simulation, it can be done by closing this convergence history window. When simulation is finished, the 'Running' indicator will turn red. Note, when the project is saved and closed, with next re-opening, the simulated results will not be reproduced.

6. Coupled cavities. Tapered structures.

KlyC has a special option that enables simulation of coupled cavities [9]. When a klystron with *m* cavities is simulated with consideration of the mode coupling; an *m* x *m* matrix will be generated in KlyC, or provided by user if the coupling coefficients were determined in simulations using other codes. Such a matrix shall be determined in a text file:

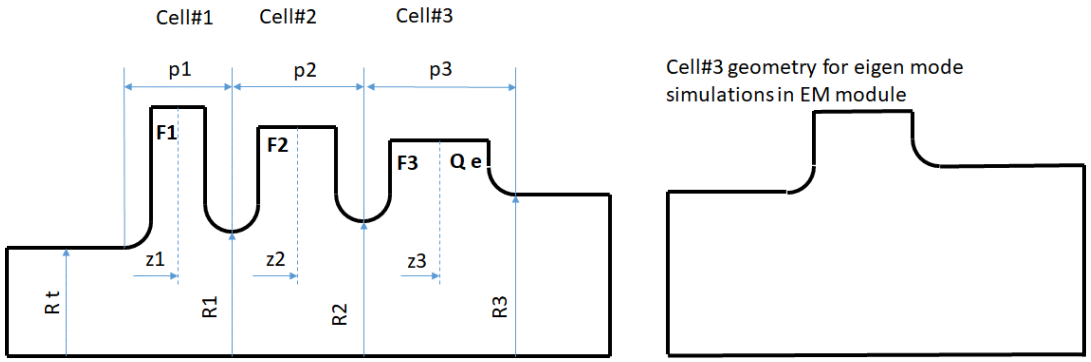
$$\boldsymbol{\kappa} = \begin{bmatrix} \kappa_{1,1} & \kappa_{1,2} & \dots & \kappa_{1,m} \\ \kappa_{2,1} & \kappa_{2,2} & \dots & \kappa_{2,m} \\ \dots & \dots & \dots & \dots \\ \kappa_{m,1} & \kappa_{m,2} & \dots & \kappa_{m,m} \end{bmatrix}$$

Based on this information and eigen parameters of the individual cells, KlyC will calculate the eigen fields and eigen frequencies of *m* coupled modes and all these modes will participate in the wave-beam interaction simulations. In the case if the multi-cell output coupler is considered, the external Q factor of the coupling cell should be specified and KlyC will calculate external Q factors of all coupled modes. Shall be noted, that eigen frequencies of the individual cells are not necessary to be identical, though their difference is recommended to keep at or below a few per cent level. In this case the coupling coefficients will be barely affected. The coupled modes option activation is controlled by the 'coupling' information window, which by default is set to zero: 

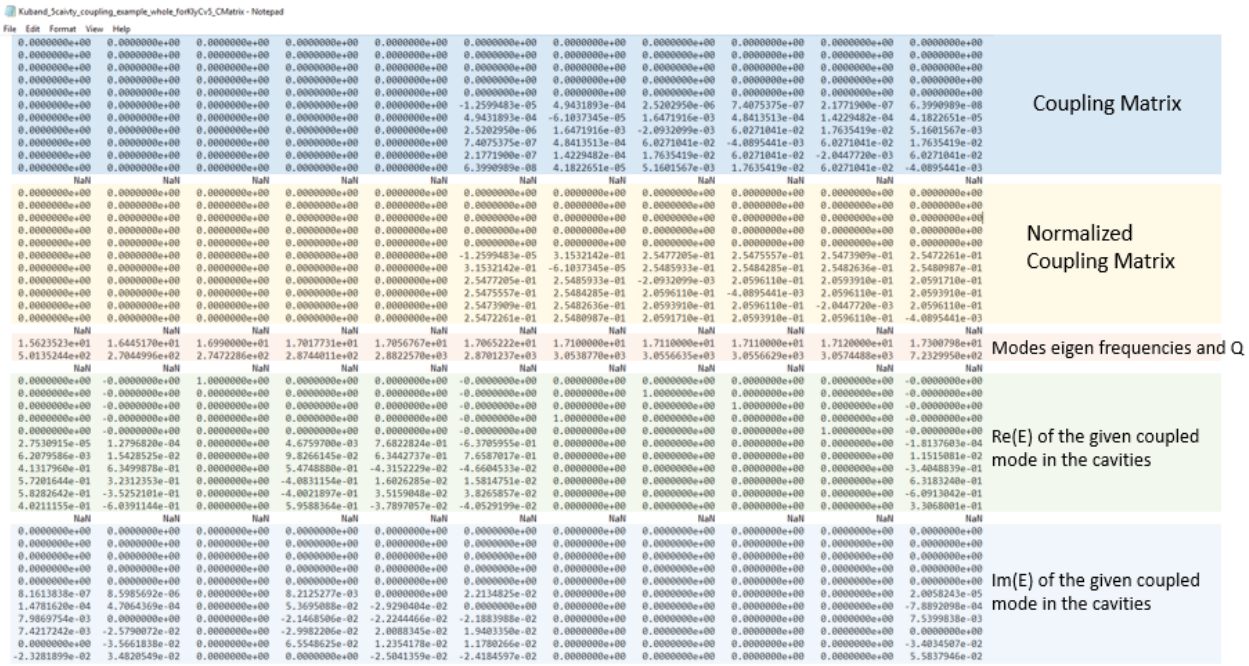
To enable the coupling cells simulations, the coupling shall be set to auto: 

. In the next picture, the geometry of the 3-cells output coupler is shown as an example. The cell with external coupling here is the last one with Qe assigned to this cell in the parameters table (cell type: -1). In general the user can assign the external coupling to any cell. Each cell has to be introduced one by one with its own geometry file and simulated in EM module (We(J): -1). Cell positions (z) and target frequencies (F) are characterized in the parameters table. The outer radius of each cell has to be re-iterated using EM module to meet the low frequency error (<0.01) in the column R(cm). Note, that the drift tubes length assign to the cell in these simulations shall be long enough, anticipating the cut-off frequency of the drifts. The information about each cell which is relevant to the coupling matrix generation is introduced in the right table. In the column 'Lc(mm/MB)' the period (p) of each cell is specified. If period is set to '0', then this cavity will be not used in the matrix calculation, however, the matrix still will have size *m* x *m*, where *m* is a total number of

cavities. If the structure is tapered, then in the column 'nose(mm)/Tp', the average tapering ratio has to be set. The tapering ratio is defined locally and is normalized to the drift tube radius. For the first cell shown in example, Tp1=(R1+Rt)/2/Rt, for the second cell Tp2=(R2+R1)/2/Rt etc. Important: KlyC does not support the negative tapering and requires geometry files to be prepared for the EM module (no KlyC E field profiles or imported 2D field maps are supported). In some cases the penultimate cavity(ies) can appear to be located close enough to the coupled cells structure (the distance is less the drift tube radius for example). In this case, the user can decide to include this(ese) cavity(ies) in the coupling matrix calculation or not. This situation is shown on a KlyC project screenshot on the previous page.

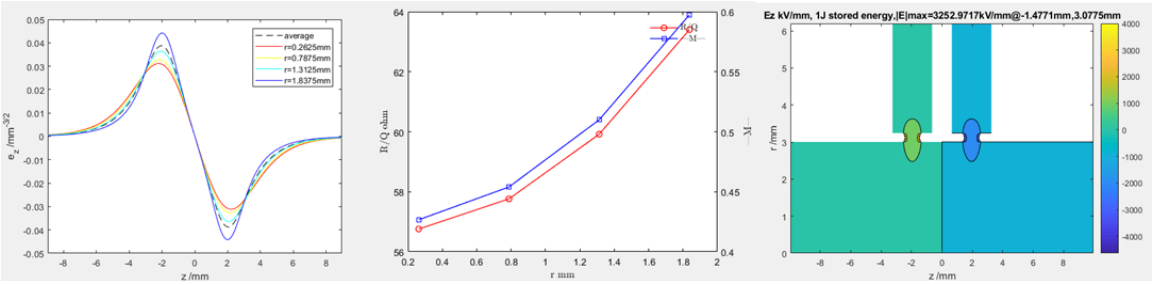


When the KlyC finishes the klystron simulations, it will generate and write a file into the project folder with coupling matrix and eigen modes information ('text output' box shall be checked to generate the file). This file will have the klc project name with '_CMatix' added to the name. Example of such a file generated after simulating the tube (see previous page with the tube project screen-print) is shown next. In this tube the output coupler comprises 4 identical cells (8-11) with constant aperture. The output matrix file contains the following information:



1. Matrix with coupling coefficients
2. Matrix with normalized coupling coefficients. These coefficients do not depend on the period length.
3. The eigen frequencies and Q factors of all the modes. The modes are listed with ascending frequencies, so that frequencies of the coupler coupled modes could appear in between the frequencies of the bunching cavities. This data can be used to benchmark KlyC results with eigenmodes found by other codes (HFSS, CST) for the same coupler topology and individual cells frequencies.
4. and 5 provides real and imaginary electric field components of the mode with eigen frequency as specified in bullet 3. For example in this case, we can see that the first column contains the values in the last 6 cavities and thus it is the lowest coupled mode. Whilst the column 3 has only one none-zero value, thus this is the uncoupled mode of the bunching cavity.

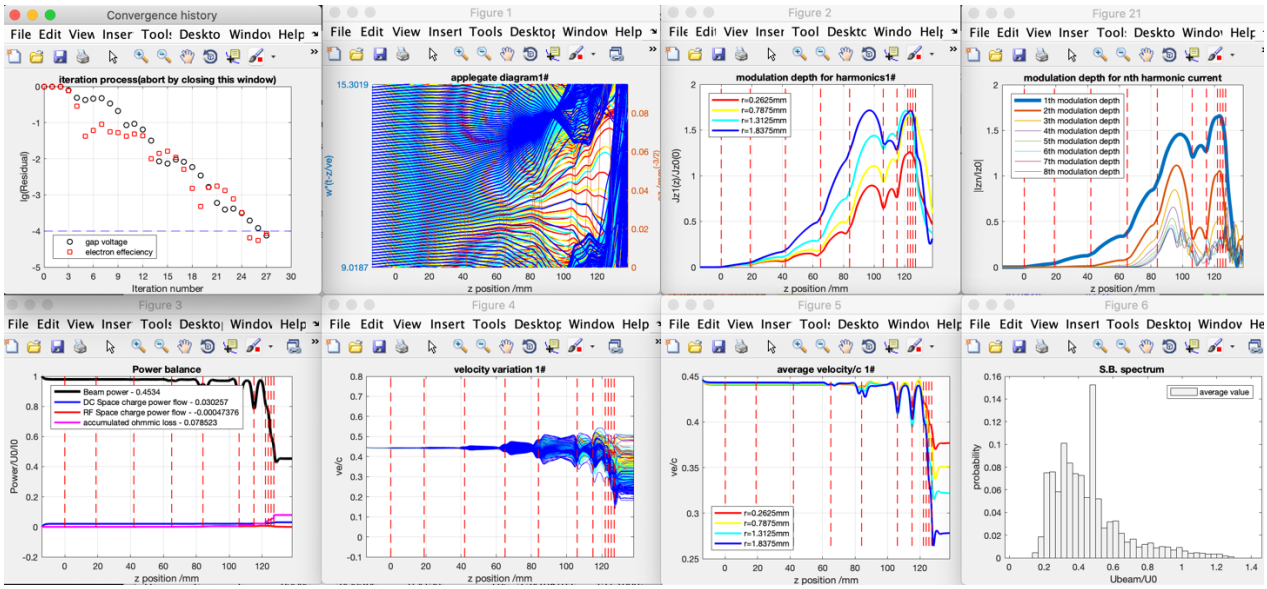
When the simulation is completed, another useful information can be found in the results table, where KlyC will report on the maximal surface field in each cell (and cavity) in the column ‘phi(d.)/ E kV/mm’.
Advanced user can elaborate methods of how to calculate the coupling matrix using results of the eigen solvers from another codes. In this case matrix with coupling coefficients can be imported into KlyC by replacing ‘auto’ in the coupling window with the matrix file name.
Initial optimization of the new multi-cell coupler is a delicate process. We may recommend to start this optimization with coupler along using the KlyC bunched beam option (see Chapter 8). In this case the first cell of the coupler shall be put at a distance (z-position) ~ 1.5-2 drift tube radius apart from the emission plane. At the beginning, all the cells are recommended to be tuned to the same frequency and the bunched beam shall have a moderate length (120 deg. RF phase) and congregation (chirp ~ 0.2-0.3). With this option, the user can change the frequency of the bunched beam manually and adjust it to the one, which will provide the best coupling to the beam (max output power). Now, all the cells can be re-tuned the same way to adjust the frequency to the designed operating frequency. From now on, the user can launch the frequency and Q external optimization using KlyC optimizer module (see Chapter 9) in attempt to achieve the best performance. When optimization is finished, the coupler can be connected to the bunching circuit and optimization of entire tube can be started.
In some cases the bunching cavities also can also be represented by a coupled cells structure. Normally the mode separation in these circuits is large enough from the very start. Thus, in the absence of the external coupling, there is no needs to use coupling matrix, as only one mode will be participating in the beam wave interaction. In this case we recommend to construct the full geometry of the multi-cell structure, specify the number of operating mode in the geometry file and use EM module to calculate the 2D field maps. In the given tube example, cavities 2-5 are the two-cells cavities operated at pi mode, see the picture below.



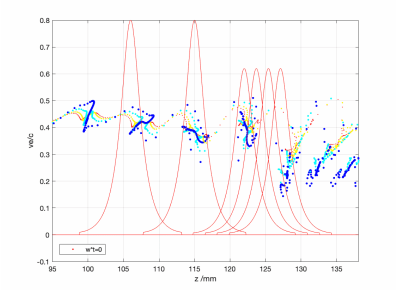
7. KlyC output graphics, animations and data.

If requested, upon completion the simulation, KlyC will generate multiple graphics and animations. The animations are generated as gif files and stored in the project folder. Below results are from example file “Kuband_5cavity_coupling_example_whole_forKlyCv5.klc”:

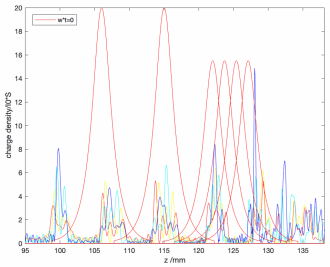
Graphical output:



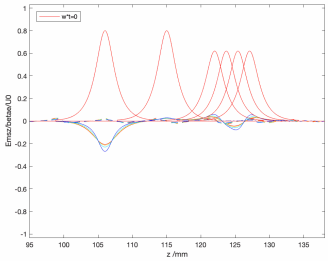
Animations:



Phase trajectory.gif



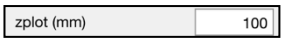
density modulation.gif



field distribution.gif

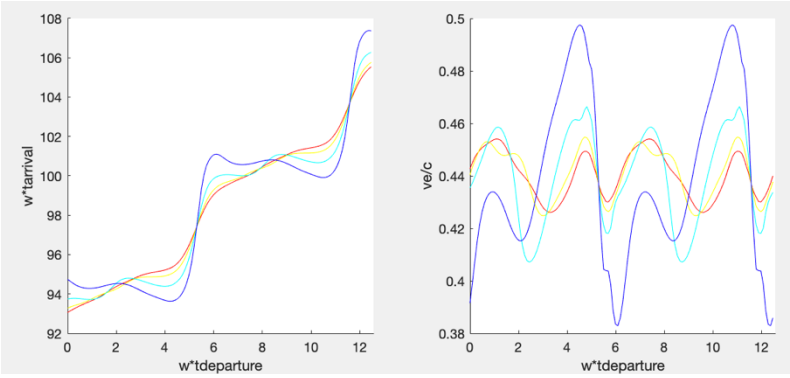
For all those GIF movies, red means innermost layer and blue is the outermost layer. The dash line in field distribution is Ez component of the space charge field.

To generate **arrival functions** (time and velocity), the 'hold on' box 

in the plot setting menu needs to be checked before simulations have been started: Next, the position at which the arrival functions will be calculated shall be specified: . 

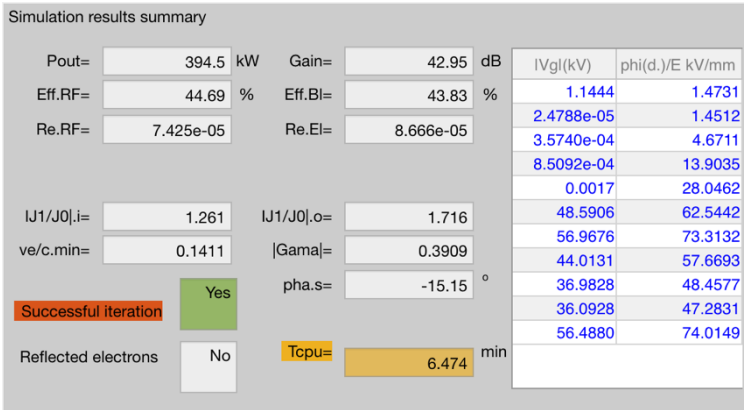
Finally the arrival function will be generated after clicking on 

.If this operations is repeated for the different zplot value, the new curves will be added to the pictures. The curves will be saved into data files (with value of zplot in the file name) if 'txt output' box is checked.



Note, these calculations require storing a lot of data in a computer memory. That is why, one may consider to use this option if only necessary. The memory cache can be emptied by clicking on 

The results of simulations are collected in the 'Simulation results summary' table:

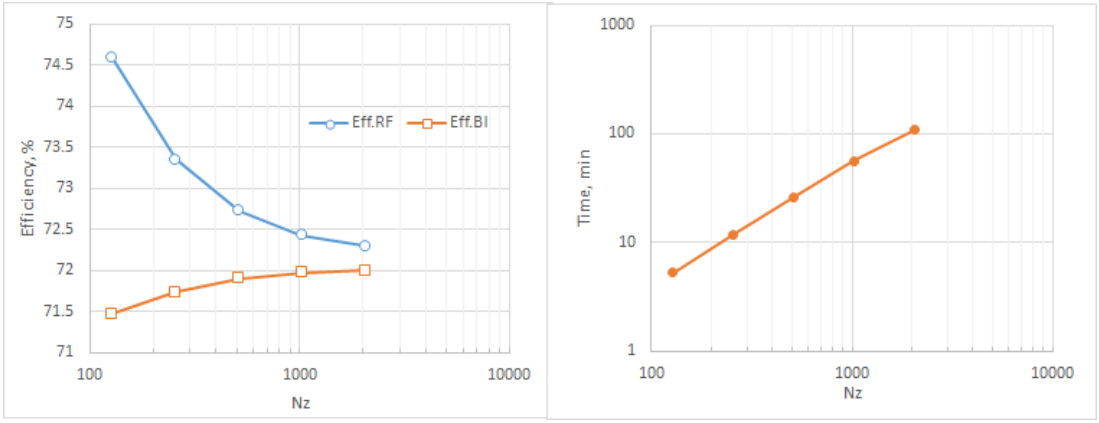


Simulation results summary

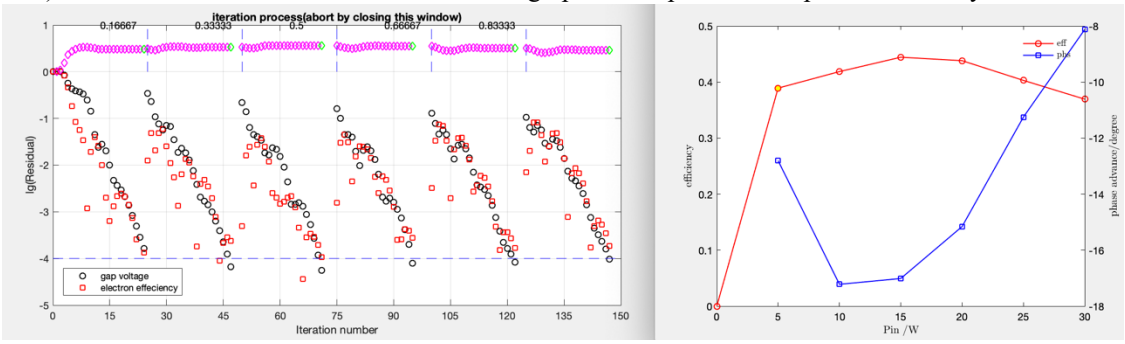
Pout=	394.5	kW	Gain=	42.95	dB	IVgI(kV)	phi(d.)/E kV/mm
Eff.RF=	44.69	%	Eff.Bl=	43.83	%	1.1444	1.4731
Re.RF=	7.425e-05		Re.El=	8.666e-05		2.4788e-05	1.4512
						3.5740e-04	4.6711
						8.5092e-04	13.9035
IJ1/J0|.i=	1.261		IJ1/J0|.o=	1.716		0.0017	28.0462
ve/c.min=	0.1411		|Gama|=	0.3909		48.5906	62.5442
			pha.s=	-15.15	°	56.9676	73.3132
Successful iteration	Yes					44.0131	57.6693
						36.9828	48.4577
						36.0928	47.2831
Reflected electrons	No		Tcpu=	6.474	min	56.4880	74.0149

KlyC calculates the RF power production efficiency by two methods. The first method (Eff.RF) is based on the direct measurement of the last cavity gap voltage. In the second method (Eff.Bl) the beam power balance is used [8]. Here, the total lost power is calculated as a sum of the spent beam kinetic energy, DC/RF energy of the space charge in the spent beam (total space charge depression) and Ohmic losses in all the klystron cavities. With increasing the model resolution, the Eff.RF will normally converge to the Eff. Bl value. However this might require significant increasing

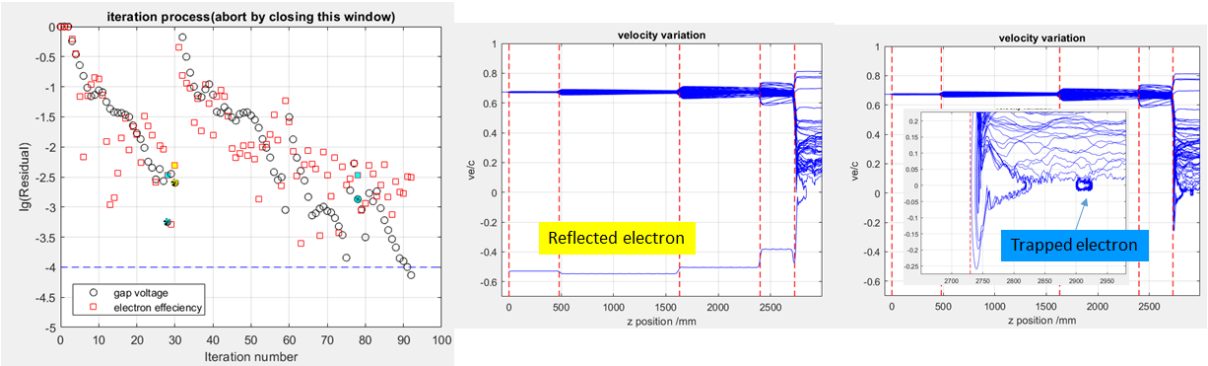
of the computation time. ‘Pout’ and ‘Gain’ in the summary table are calculated using balanced power. Here below is the convergent curve calculated by KlyC regarding to one of the HE Klystrons published in [8].



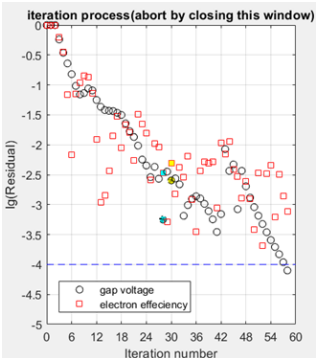
To calculate the power transfer curve in automated regime, check the ‘Power ramp’ box and select the number of points for simulation: Power Ramp 6 Next specify the value of the maximum power to be used: Pin (W) 30.000 , set the itearations number to be larger than N_points x N_1 (N_1 is anticipated number of iterations needed for single simulation) and start simulation. Here below shows the graphical output for example Ku-band Klystron.



In the presence of reflected electrons, KlyC will have problems with convergence. These reflected electrons could be virtual: the ones that appear shortly during the iteration process only; or the real ones which will persist. KlyC indicates two types of abnormalities: **reflected** electrons (circles colored in yellow during iterations process), those who reached the emission plane and **trapped** electrons (circles colored in blue), those who stay in the simulation volume for more than 10 expected flight time.

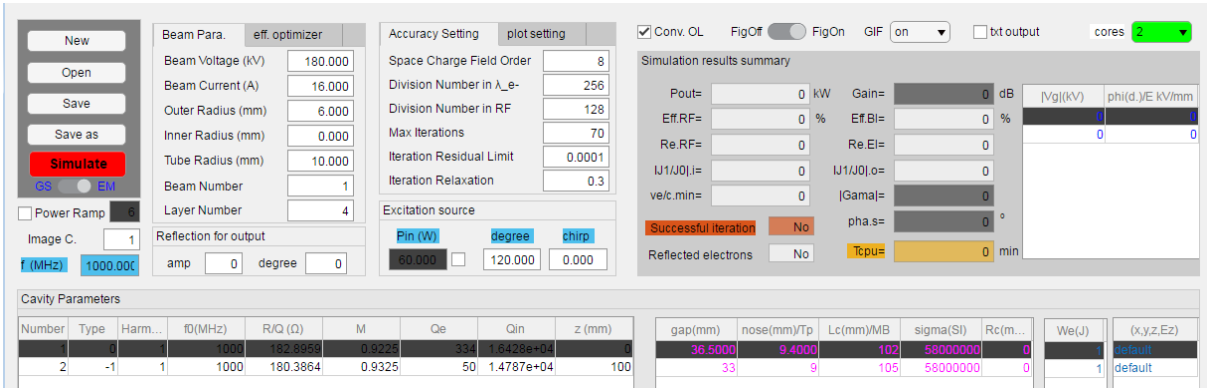


If these effects are numerical artefacts (virtual reflected electrons), the user can try to mitigate them by adjusting the value of relaxation parameter and/or changing the number of layers in 2D simulations. Ultimately, the user can specify position of the plane at which the reflected electrons will be absorbed. The position of the absorbing plane is specified in the plot menu using zcut(mm) zcut (mm) 95. In the given example, zcut was set to be between the last bunching and the output cavity and provided smooth convergence.



8. Bunched beam as a power source.

KlyC allows the user to simulate an RF circuit excited by a bunched beam [9, 10]. This option can be used for an IOT design, or for individual studies of special RF output structures in electron devices. The cavity types here will be limited to type '1' and type '-1', meaning no input cavity. To enable this option, the 'Pin' box shall be unchecked which will modify the KlyC GUI window as shown below:



In the given example, we have used the output cavity of one of the L-band klystrons that we have designed introduced before. Even the parameters of first cavity in the table are not used (colored in dark grey), the user still has to specify the cavity position, as it will be used as a position of the emission plane.
The modulated current will be represented by individual bunches with constant charge distribution along the bunch. The bunch separation is defined by the operating frequency and the bunch length is specified by the user in terms of the operating wavelength RF phase:

In addition the user can choose if the bunch should have velocity dispersion (congregation) along the bunch length using:

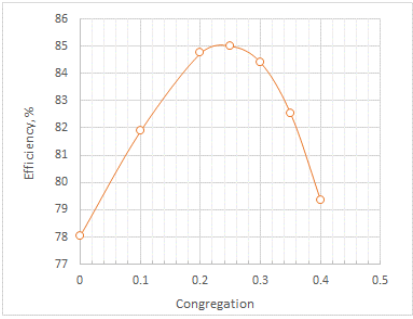
(which in the input cavity mode instead gave a radial dispersion of the beam current density). In this case KlyC will generate congregated bunch, where the velocity of the

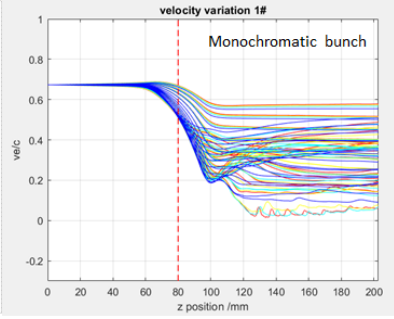
bunch head is lower than the velocity of the bunch tail. The amplitude of congregation (0<chirp<1) will be used to generate the velocity dispersion:

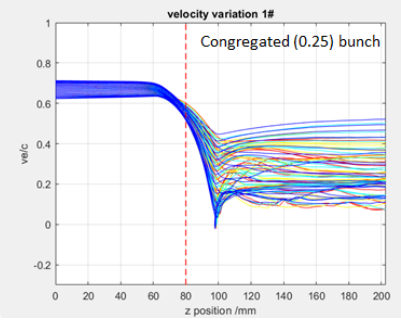
$$U(t_0) = U_{aver}[1 + chirp \cdot \sin(\omega t - \pi)], 0 < \omega t < 2\pi$$

$$I(t_0) = \frac{I_{aver}}{2\alpha}[\text{sign}(\omega t - \pi + \alpha\pi) - sign(\omega t - \pi - \alpha\pi)], \alpha = degree/360°$$

so that the average kinetic energy of the bunched beam is identical the equivalent DC beam kinetic energy. In the next example we have studied how the RF power extraction efficiency depends on the bunch congregation amplitude:







9. KlyC internal optimizer module.

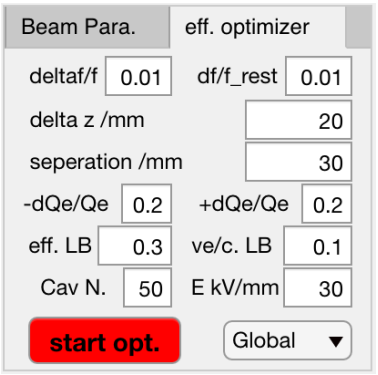
Two types of optimizers are supported in KlyC. The resonant frequency, positions of each cavity and Q_{ext} of the output cavity will be varied to approach the maximal RF production efficiency. Any optimization is a time consuming process. Therefore, an appropriate tube design is recommended to be used to start with optimization. Such a design can be done manually.

KlyC suggests two methods for the optimization: genetic algorithm (GA) and pattern search algorithm (PSA).

GA: https://en.wikipedia.org/wiki/Genetic_algorithm

PSA: https://en.wikipedia.org/wiki/Pattern_search_(optimization)

In general, GA method uses large group of the individuals and their evolution. Therefore, it is a global search method which is usually rather time consuming. Each new generation is prepared by its parental generation through the selection, crossover and mutation operation to ensure its improvement of fitness and diversity. The optimization parameters are specified in the 'eff. optimizer' window:

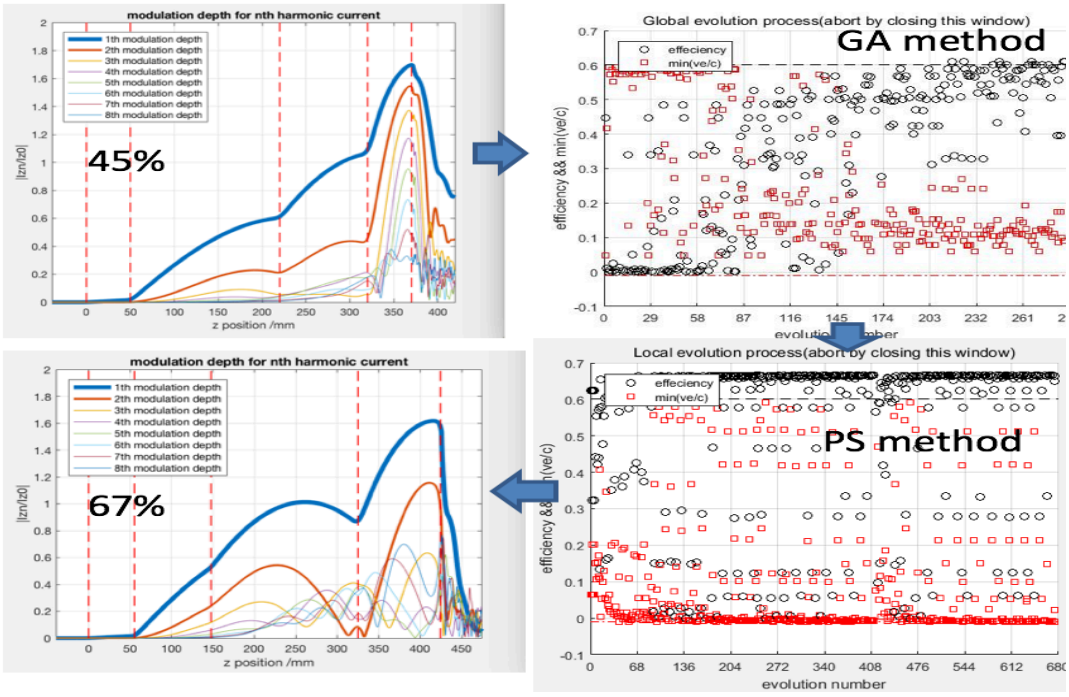


The parameter 'Cav. N' setting allows to optimize either an entire klystron (N is equal to the total number of cavities *m*), or for separate optimization in two groups of cavities, where first N cavities will be treated differently from the rest of the cavities. This option was specially introduced to allow separate optimization criteria for the bunching circuit and the output multi-cell circuit. The first group of cavities parameters (frequency and position) will be selected from the values specified by user: 'deltaf/f' – normalized frequency detuning window, and, delta z/ mm – cavity absolute position deviation window. User shall also specify 'separation /mm', this will allow to exclude the position selection, if the distance between two adjusted cavity gaps centers is below specified value. The second set of cavities will only use the frequency modifications from the window that is specified in 'df/f_rest' box. Whilst the relative cavities position in this set will not be modified and all the cavities will be moved as a bulk when the drift tubes length in the fist cavities set is changed. Note, the separation between the two sets of cavities shall be larger than the one specified in 'separation /mm' box. The external Q factor modification window can be set to be asymmetric using '-dQe/Qe' and '+dQe/Qe' values. Next, the user has to specify the minimal efficiency limit: 'eff. BL'; minimal accepted electron velocity in the output gap area: 've/c. LB' (we recommend to set ve/c. LB not below -0.2) and maximal surface electric field 'E kV/mm'. Any solution where these parameters exceed the specified limits will be discarded, as well as non-converged solutions and the ones with reflected electrons. The accepted solutions will be saved into temporary file in the project folder, so that user can analyze them later.

When the optimization parameters setting is completed, the optimization will be launched after clicking on 'start opt.' button. KlyC will ask user the name of the project where the optimized tube klc file will be saved to. Next, the optimizer progress window will pop up to show the process evolution. In this window, the minimal electron velocity and

efficiency for every accepted solution will be shown. The optimization will be stopped automatically if the process is saturated. However, the user can decide to interrupt optimization at any point by closing the optimizer window (please give KlyC some time to close the process smoothly). By finishing/closing optimization, KlyC will automatically update the klystron design parameters table accordingly to the set which delivered highest efficiency and save these parameters in the specified klc file.
Another optimization option is a 'Local' (PSA) optimization. It can be selected from the optimization dropping down menu:

The local method uses similar setting as a Global method. In PSA, only one initial case is used to start the optimization. This method does not require a gradient calculation to avoid the optimizer to converge to a numerical pole. For a large loop of one iteration, neighborhood points will be taken into consideration to determine the next step. One step here is one generation. Considering that initial klystron design is already in a good shape, the Local optimization converges by far faster than Global optimization. In example below we illustrated two optimization made by KlyC. The initial klystron design was quickly prepared by positioning bunching cavities at the local maxima of the RF current modulation curve delivering 45% efficiency. Next, the GA method was used. It showed slow convergence and was interrupted after 280 iterations delivering 62% efficiency. The new klystron setting were used to start a final optimization with the PSA method, which after about 100 iterations converged to the settings that provided 67% efficiency and a COM bunching circuit [15]. To speed up the overall optimization process, we may recommend the use of the 1D/GS environment as a first stage and then use the 1.5D/EM environment for the second stage of optimization.



In the optimizer menu KlyC suggests another service function: automatic simulation of the klystron bandwidth plot. This option will be activated when 'Bandw' is selected in the dropdown menu. In this case 1+2*'Cav N.' frequency points between (1-deltaf/f) x 'f (MHz)' and (1+df/f_rest) x 'f (MHz)' will be used for bandwidth simulation. A text file and bandwidth figures (efficiency and RF phase advance) will be generated automatically. The klystron output table and operating frequency will be updated automatically for the frequency where the highest efficiency has been reached. This simulation can be aborted online by closing the report window or by toggling down the 'Switch' 

.

10. The batched jobs

Sometimes there are just too many simulations that you don't want to run it one by one manually. These simulations may be a parameter sweep, sensitivity analysis or just a few different tubes. If all the projects (klc and other supporting files) are located in the same folder, one can use the batched job simulator option in KlyC to run them one by one. To start with, one of the projects shall be opened in KlyC GUI. Next, click on 'RunAll' button to start the batch simulations. The simulation is organized by alphabetic order of the files names. The total number of the klc files and simulation progress will be indicated in the instrumental panel ('Prog.' meter). Batch can be aborted by switching the toggle to 'Off' position. Please wait until the current job is finished. The summary for batch simulations will be saved in 'txt' file. Some basic simulation results are saved there for comparison. For each simulation, the results can also be saved if 'txt output' box is checked.

Some users reported that it is inconvenient to generate multiples of similar klc file directly in the KlyC GUI. We may recommend to open klc file by any text editor and learn the format and structure of the file, which is enough self-explanatory. Next, one can generate a script using any other code that can prepare klc file automatically with input parameters modified by user at his convenience.

11. Recommendations for MBK simulation

KlyC supports Multi- Beam klystron simulation [11, 12]. This option will be activated if in a **'Beam Number'** window the specified value is larger than one. This MBK simulations requires that filed map shall be imported. Thus, user has to ensure that during simulation in HFSS or otherwise, the major Z axis of the coordinate system is in line with one of the beamlets (drift tube) axis. The imported electric field 3D map will be examined by KlyC and the azimuthal field variation in the beam area will be averaged and a 2D map will be generated.

12. Sharing & Scaling

There are two special functions which are quite useful when the current simulated Klystron has to be shared with other people and/or transformed into new Klystrons design with different specifications.

By pressing 'share' button 

, the current klc file and all its supplementary files (coupling matrix file, field file and results file if applicable) will be saved into a sub-folder which is located at a working folder. Such sub-folder could be zipped and sent to other colleagues.

By pressing scaling button 

, scaling transformation based on PSP (parametric scaling procedure) will be launched [13]. The current klc file will be a destination file where the parameters of the new goal Klystron will be defined. The user can change the voltage, current, operating frequency, drift tube & beam radii and the impedance of the cavities. A popped-up window will let you select the existing Klystron design which will be used as a basis for scaling. If the topologies of the original and new Klystrons are identical (number of cavities, type of cavities, and harmonics of the cavities), the scaling will be done almost instantly.

The scaled Klystron will overwrite the current klc file and will be automatically saved. One may wish to save the design prepared for scaling with some different name before the procedure is activated.

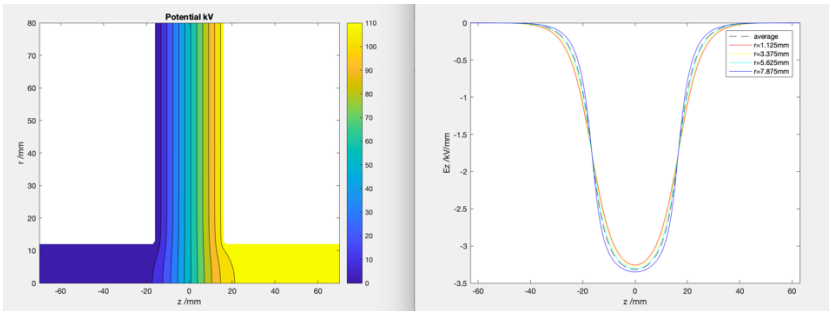
13. Electro-static simulation with bunched beam

In order to facilitate the simulations of a multi-stage Klystron, a DC module was introduced into KlyC. For example, the DC gap is defined as below in one of TS MBK simulations.

ber	Type	Harm...	f0(MHz)	R/Q (Ω)	M	Qe	Qin	z (mm)	We(J)	(x,y,z,Ez)
5	1	0	1000	99.9956	0.9000	100000	6554	704.5000	-1	DCgap0

For such a DC gap, type should be '1' and harmonic should be '0', f0,R/Q,M,Qe,Qin will not be used for this analysis, still some numbers be filled into the table. 'z' should be the position of the DC gap centre and cavity geometry file text is specified in '(x,y,zEz)'. 'We(J)' should be put as '-1' to indicate the geometry of DC gap is used.

```
115     1       1       0
-70     0       0       0
-70     12      0       0
-16     12      0       0
-16     80      0       0
16      80      0       115
16      12      0       115
70      12      0       115
70      0       0       115
-70     0       0       0
```

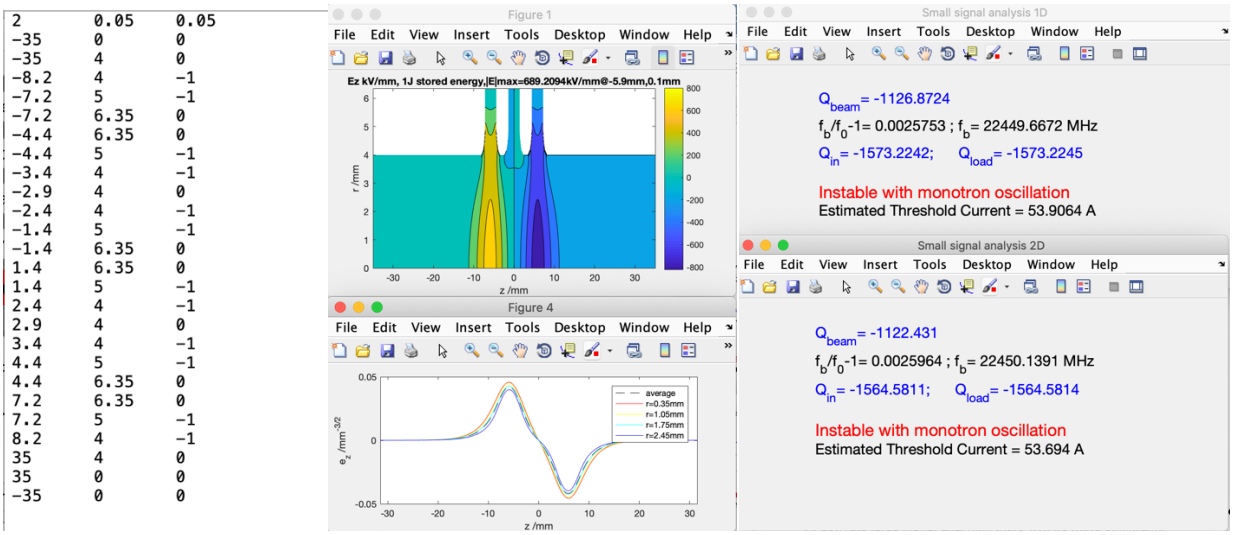


In the text file, the first line specifies the total gap voltage (absolute value), dz/mm, dr/mm, '0' will not be used. From second line on, the geometry of the DC gap is defined using the same algorithm and primitives as in EM module. Here the last column is a potential on that point of the segment. If the adjacent point has different potential, the segment defined by these 2 points will give a secondary Nueman Boundary, meaning that electric field is parallel to this segment. Notice that such a boundary will only be supported for the line segment, which is parallel to the x or y axis. Press 'Update Cavity' button to check if the DC gap is correctly prepared.
For the simulation and benchmark results regarding TS Klystrons equipped with DC gap, please refer to [11].

14.Monotron oscillation simulation

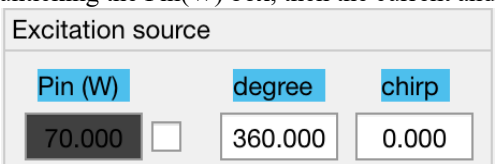
Monotron oscillation is a self-excited instability which is associated with longitudinal interactions between the electron beam and TM0,N, modes in a cavity. The small and large signal analysis of specified resonant modes are introduced into KlyC. Below is an example how monotron oscillation is analyzed in KlyC.

In this example we used the coupled cavities triplet.



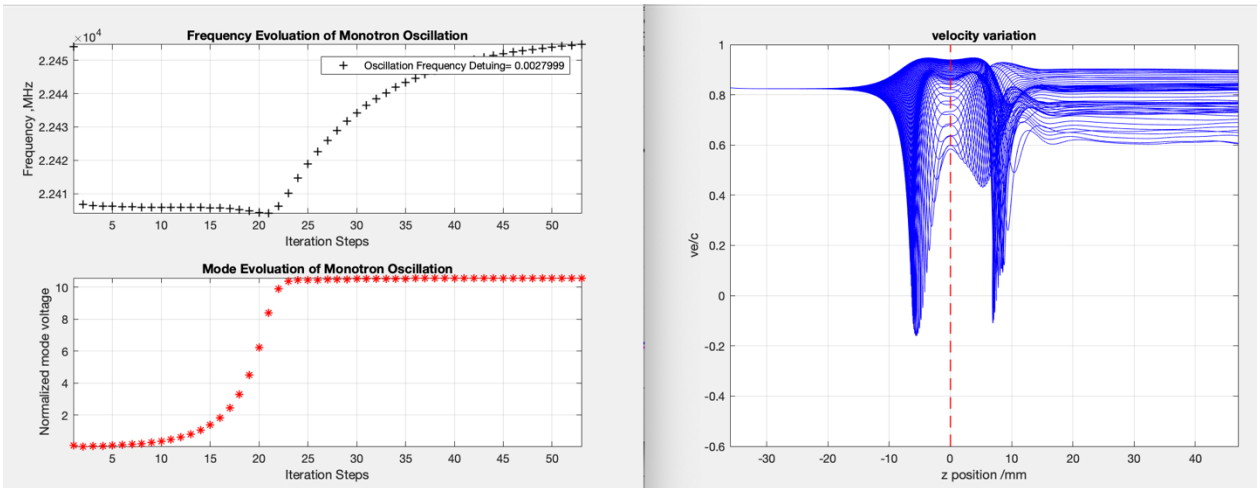
When 'Update Cavity' button is pressed, there will be text information in the results window about possible monotron oscillation calculated using small signal theory. It includes the quality factor for beam loading and the oscillation frequency. If there is a risk for monotron oscillation, a highlighted (red characters) warning message will be presented. Please note, that small signal analysis is supported when the normalized electric field is available for KlyC, and, the majority of the cavities will not have such a problem.

To activate large signal analysis the sequence is more complicated. First, the IOT module should be activated by unticking the Pin(W) box, then the current and voltage should be set to be DC:



The cavity number should be set to '2', so actually only the 2nd cavity is considered under monotron analysis. The resonant cavity for monotron analysis should be taken as the output cavity, so type should be '-1'. Qe should be set up as a very large value if there is no coupler for the analyzed cavity. The frequency should be set as 'resonant frequency' or 'start oscillation frequency' since both of them are quite close to the oscillation frequency in large signal regime.

Under those conditions, large signal simulation for this monotron oscillation could be launched by pressing 'Simulate' button; If current is larger than threshold current, the mode voltage will be increased during the iterations and then saturated.



The simulated oscillation frequency will be updated in 'f (MHz)' and Ohmic losses in the cavity will be displayed in the 'Eff.Bl' window. More information about the algorithm for monotron analysis could be referred to [14].

This manual concerns the KlyCv6.1 version, which was compiled at 1/12/2021. Please check  for the KlyC version information.

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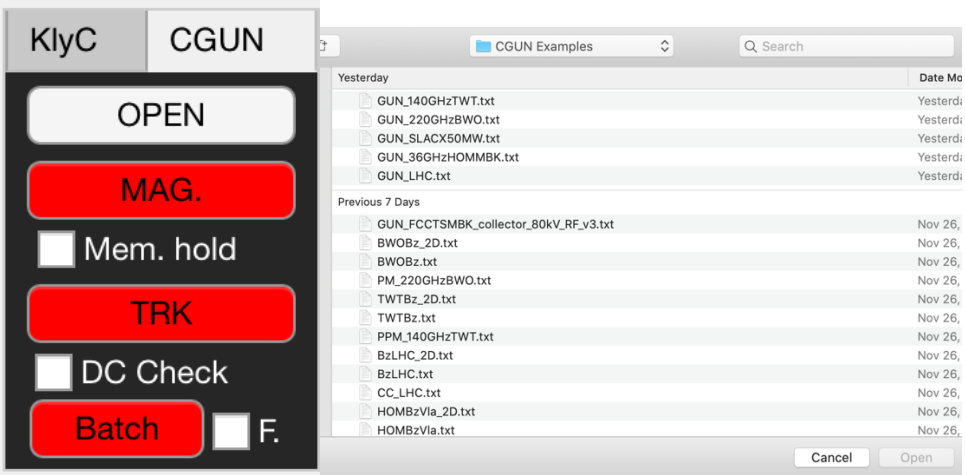
APPENDIX: CGUN

I. Getting started

Open KlyC as stated earlier, You will find the CGUN Tab in the top left GUI 

for version 6.1 and above. The 2D optics module will then be accessible,



Comparing with the KlyC module, CGUN is still based on input file operation, therefore, most of the file editing and establishing will be based on the default TEXT editor in your system.

By pressing the OPEN button (

), you can open any of the example files provided in the 'CGUN examples' folder to start editing your input file. It's not recommended that you make an input file on your own since some minor mistake may prevent you from launching the simulation successfully.

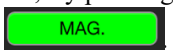
We will not go into technical details of the algorithm for CGUN in this user manual, but it is worth mentioning that there are some new features in CGUN compared to other 2D GUN codes available in the scientific community or commercial market such as EGUN, DGUN, etc. CGun has the following features:

1) Supports both WINDOW and MACOS, possibly extended to LINUX.
2) Free access to the community upon request by email
3) Easy execution and user-friendly GUI implemented into KlyC
4) Support 2D magnetic module as integrated part of CGUN
5) No software limitation for large problems (from gun to collector, for instance), parallel computation supported
6) External electric field could be generated or imported for complex problems such as collector analysis
7) Batch simulations supported for parameter sweep or optimization
8) Secondary emission model supported
9) New features could be added more conveniently in the future for specific purposes

CGUN is still based on the process of reading and executing input files which should be edited in the required format demonstrated in the following 2 sections.
In section II, an example input file for magnetic simulations are demonstrated; In section III, an example of an input file for a beam optics simulation is demonstrated; In section IV, Batch simulations will be addressed. More examples can be found in the examples folder attached with KlyCv6 installation package.

II. Magneto-static Module

For magnetic simulation, By pressing 

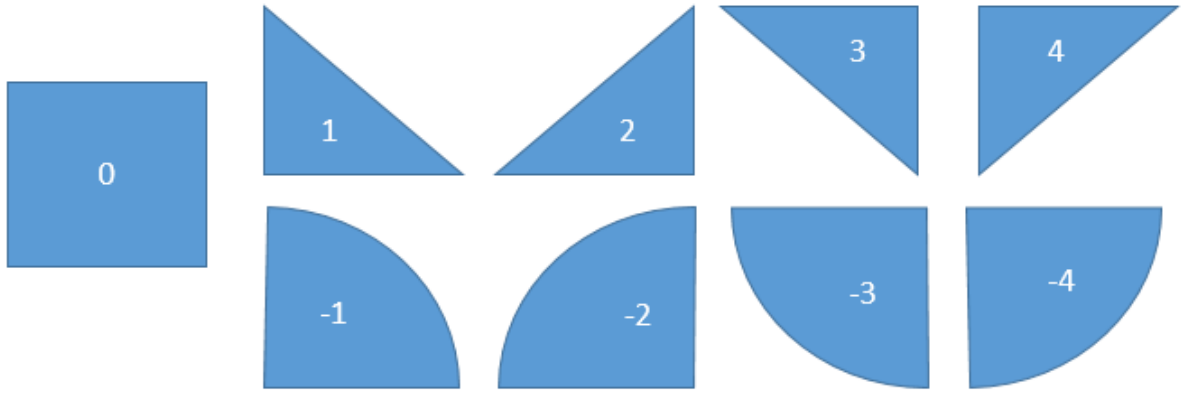
button, an example file can be loaded and then run when the button turns to green 

Magneto-static simulations will first generate the magnetic matrix and then solve it before displaying the graphical results.
Example file (CC_FCCTSMBK_80kV.txt,) regards the coil design for a 0.4GHz, 1.2MW FCC Two stage MBK can be found in the example folder and opened showing the text below,

```
cores
-250    -200    100     500     10      5       0       0       0       5000    0
2050    2100    320     500     10      5       0       0       0       5000    0
-250    2100    500     530     10      5       0       0       0       5000    0
-200    -160    320     490     20      10      0.99004 0       0       1       0
-110    -70     320     490     20      10      0.94022 0       0       1       0
4       44      320     490     20      10      1.29956 0       0       1       0
124     164     320     490     20      10      1.36104 0       0       1       0
250     290     320     490     20      10      1.79352 0       0       1       0
414     454     320     490     20      10      1.48506 0       0       1       0
534     574     320     490     20      10      1.23702 0       0       1       0
610     650     320     490     20      10      1.05152 0       0       1       0
730     770     320     490     20      10      1.23702 0       0       1       0
850     890     320     490     20      10      1.36104 0       0       1       0
970     1010    320     490     20      10      1.67056 0       0       1       0
1120    1160    320     490     20      10      1.36104 0       0       1       0
1240    1280    320     490     20      10      1.23702 0       0       1       0
1330    1370    320     490     20      10      1.23702 0       0       1       0
1450    1490    320     490     20      10      1.23702 0       0       1       0
1570    1610    320     490     20      10      1.23702 0       0       1       0
1660    1700    320     490     20      10      1.33666 0       0       1       0
1780    1820    320     490     20      10      1.23702 0       0       1       0
1955    2045    320     490     20      10      1.36104 0       0       1       0
1580    2080    0       100     10      5       0       0       0       1       0
2080    2300    0       200     10      5       0       0       0       1       0
2300    2900    0       350     10      5       0       0       0       1       0
shape
fielddisp 2
```

ksimN 100
Rlimit 0.001
iter 0.3
Bzname FCCBz2
Mate ironCST
zt -300 0.5 3300
cigma 5.8E7

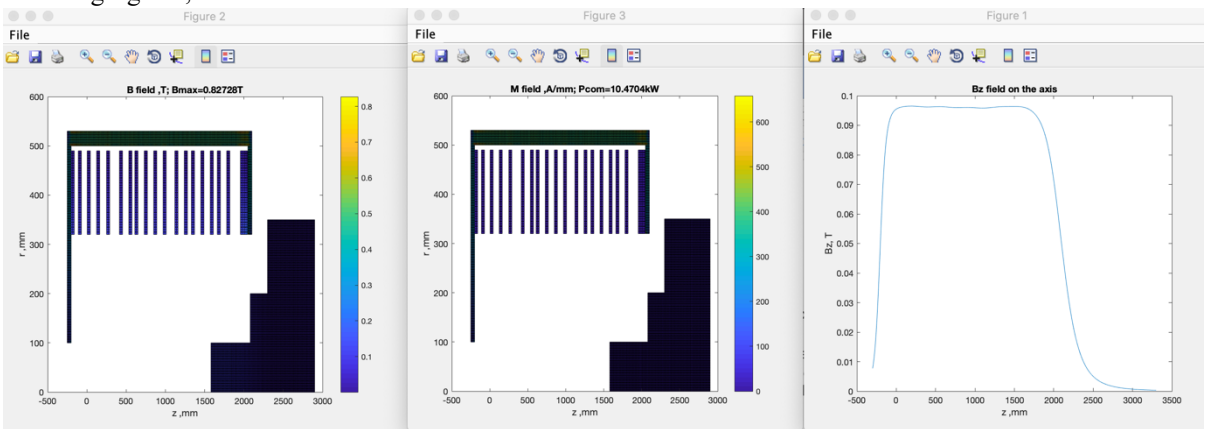
The structure of the input file will be elaborated here,
Cores: keywords reserved, null
From 2nd line to the keywords shape: To define the geometry and parameters of the current coils or magnets, a single solid is defined in each row, the 11 values from beginning to end indicates:
1)Minimal z position, mm
2)Maximum z position, mm
3)Minimal r position, mm
4)Maximum r position, mm
5)Mesh size along z, mm
6)Mesh size along r, mm
7)Azimuthal component of current density (J_a), A/mm^2
8)z component of residual magnetization ($B_{z0}=\mu_0 M_{z0}$), T
9)r component of residual magnetization ($B_{r0}=\mu_0 M_{r0}$), T
10)relative permittivity (u_r): When u_r=0, nonlinear iteration for magnetic material will be deployed, otherwise, linear solution with definition u_r of will be utilized.
11)Geometry control:
If this value is 0, a rectangular shape will be adopted.
If this value is 1, a triangle with right angle at quarter 1 will be reserved;
If this value is 2, a triangle with right angle at quarter 2 will be reserved;
If this value is 3, a triangle with right angle at quarter 3 will be reserved;
If this value is 4, a triangle with right angle at quarter 4 will be reserved;
If this value is -1, a quarter of circle with right angle at quarter 1 will be reserved;
If this value is -2, a quarter of circle with right angle at quarter 2 will be reserved;
If this value is -3, a quarter of circle with right angle at quarter 3 will be reserved;
If this value is -4, a quarter of circle with right angle at quarter 4 will be reserved;



fielddisp: 0--nothing will be plot; 1—only plot Bz(z,0); 2—plot everything
ksimN: maximum iteration rounds if nonlinear simulation is launched
Rlimit: residual limit for nonlinear iterations
iter: relaxation coefficient for nonlinear iterations
Bzname: When it's defined as 'filename', filename.txt to save (z, Bz) field mm, T; filename_2D.txt to save Bz(z,r) and Br(z,r) in mm, T with format z/mm, r/mm, Bz/T, Br/T, for all the blocks defined before. Notice that in the condition that last few solids defined as non-source solid, J_a=0, B_{z0}=0, B_{r0}=0, we could use the 2D field mapping in this area as external B-field for beam optics simulation.

Mate: material used to substitute the one with u_r defined as 0. B(H) curve is defined in such text files. H, A/mm, B, /T; Constant magnetization extrapolation will apply if magnetic field is out of the scope of definition.
zt: Bz field on the z axis to be calculated, mm
cigma: conductivity of the solid multiply by filling factor squares, to calculate ohmmic loss on metal where current is passing through, $ohm^{-1}m^{-1}$.

A brief summary of the simulation results produced upon executing such an input file, is demonstrated in the following figures,



In these plots, B field and M field distribution can be found. The Bz(z) profile on axis is also displayed. The files to store the information about Bz(z) can be found in the folder where the input file is located. Other important information like maximum B field and power consumption in metals are also shown in the title of the figures.
Since an integral method is used, memory consumption in the process of generating the matrix is normally considerable. To ensure a mainstream PC/MAC (16 GB internal memory) can support this matrix generation, usually 10,000 mesh cells will be the physical hardware limit, while for a reasonable matrix-establishing time, 5,000 mesh cells should be considered as upper limit.
According to our analysis, for most problem, 2/3 of the total simulation time will be spent on the matrix generation for linear problems, therefore, if the next magnetic simulation will not change the geometry of the system,

☑ Mem. hold could be kept ticked to skip this process in order to speed up the simulation.

Other examples (input files) of magneto-static simulations are also provided in the library with the software, which includes:

1. CC_50MWXband.txt	for X-band 50MW HE Klystron, current coil
2. CC_36GHzHOMMBK.txt	for 36GHz HOM MBK, current coil
3. CC_LHC.txt	for 0.4GHz HL-LHC HE Klystron, current coil
4. PPM_140GHzTWT.txt	for 140GHz FW TWT, nonlinear, permanent magnet
5. PM_220GHzBWO.txt	for 220GHz Folded waveguide BWO, permanent magnet

III. Beam optics Module

As mentioned in abstract section, the electro-static module is implanted in the optics module. For optics simulations, by pressing the 

button, an example file can be found and run when the button turns to green 

. Beam optics simulations will be performed in several numerical interactions combined with trajectory simulations and electrostatic simulations in each iteration. If the electrostatic simulation is to be done without the presence of electrons, tick the 

to proceed to the fast evaluation.
Example file (GUN_FCCTSMBK_gun_80kV.txt,) regards the electric gun design for a 0.4GHz, 1.2MW FCC Two stage MBK and can be found and opened showing the text below,

```
cores 1
0       0       0       -14
0       8       0       -14
0       8       1000    -14
0.8     9       1000    -14
0.8     14      0       -14
19      14      0       0
19      10.8    0       0
100     10.8    0       0
100     0       0       0
0       0       0       -14
shape
Nz 2000
Nr 300
figureplotDC on
Bzfile FCCBz2
zsp -100 2000
asp 0.06 0.06
Bac 1 1
Bzshift 0 1 0 0
figureplotMag on
Vr 14
Lr 19
Nb 60
Nc 1
zb0 0
Rc -1
re 4 7.6
I0 1.95
Ev0 0
alfat 0
Vpt 0
Nt 4
iter 0.5
iters 0.5
Nlimit 100
Rlimit 0.001
NcL -1
zc0 100
Iper 0.98
zmonitor 20 5 90
SEY 0 0 300 0.42 20 1 1600
figureplotBE on
```

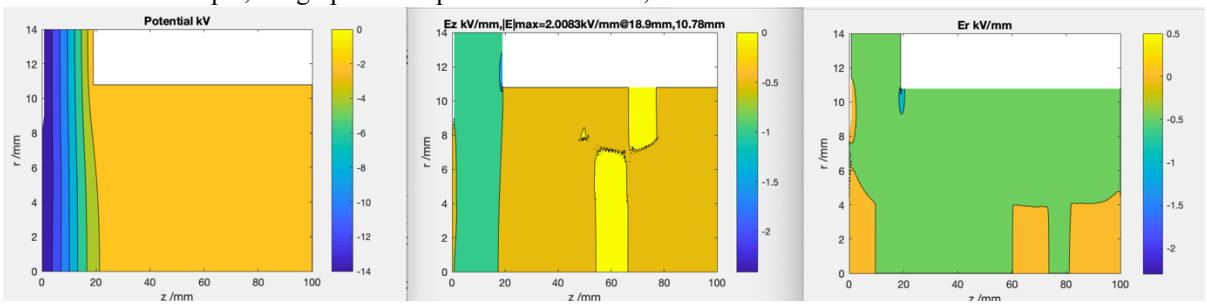
The structure of the input file is organized as,
Nz: Number of mesh cells longitudinally in whole calculation domain.

Nr: Number of mesh cells radially in whole calculation domain.
figureplotDC: Figure plot on or off for final electrostatic results.
Bzfile: Bz field distribution (T,mm) on the axis will be imported with the name Bzfile.txt. Bzfile_2D.txt will be imported instead when fourth number of Bzshift is negative.
zsp: mm, when Bzfile is empty, zsp and asp will be used to define axial magnetic field profile in input file.
asp: T, axial magnetic field. The length of asp should be identical to zsp.
Bac: coefficients for how much self-excited magnetic field [Ba, Bz] are considered in optics simulations.
Bzshift: 4 variables used to make modification of external magnetic field. z+Bzshift(1), mm; Bz*Bzshift(2)+Bzshift(3), T; Bzshift(4)=0, Expanding axial magnetic field in simple order; Bzshift(4)>0, Expanding axial magnetic field in complex order; Bzshift(4)<0, 2D $B_z(z,r)$ and $B_r(z,r)$ will be imported with the name Bzfile_2D.txt.
figureplotMag: Figure plot 'on' or 'off' for final magneto-static results.
Vr: eV, this positive value will be used as initial emission kinetic energy of electrons. The direction of emission velocity vector is perpendicular to emission surface.
Lr: mm, when Lr is positive, Lr/30 will be used as diode distance to calculate space charge limit emission current abide by Child's law. Otherwise (Lr is zero or negative), fixed emission current model will be used.
Nb: Number of emission points on the cathode surface.
Nc: Number of groups for optics simulations, usually it should be the same as computation cores but that is not mandatory.
zb0: mm, the original point for the cathode surface.
Rc: mm, when Rc>0, spherical cathode surface could be considered, otherwise, planar cathode surface is considered.
re: mm, inner and outer radius of emission area on cathode surface, respectively.
I0: A, fixed emission current or space charge limited current in the first iteration.
Ev0: row variables for Energy spread, original emission energy*(1+Ev0), the number of variables should be equal to Nc.
alfat: 6 variables to describe the external field in certain region , V(alfa1)-V(alfa2)=alfa(3)+alfa(4)*r+alfa(5)*r^2+alfa(6)*r^3; mm,mm, kV, kV/mm, kV/mm^2, kV/mm^3.
Vpt: kV, voltage spread applied in certain region between alfa(1) and alfa(2) , the number of variables should be equal to Nc. Put alfat=0 and Vpt=0 to deactivate external field import.
iter: relaxation coefficient for charge density, should be positive number.
iters: relaxation coefficient for emission current density in space charge limit emission model, should be positive number.
Nlimit: maximum step for gun iterations.
Rlimit: residual of charge density between iterations set as the convergent criterial.
NcL: number of segments for collector heat dissipation analysis, when abs(NcL)>2, power dissipation diagnosis will be activated; when NcL>=0, current density plot defined by zmonitor will be activated.
zc0: mm, starting point for power dissipation analysis, end point will be determined by the far end of the structure;
Iper: the envelop enclosed with such percentage will be taken to statistics when 1>Iper>0
zmonitor: mm, the locations where the envelop defined by Iper will be calculated.
SEY: Secondary electrons emission settings determined using the Vaughan model, SEY(1)—maximum rounds of secondary emission electrons will be considered; SEY(2)—Es, eV, eV; SEY(3)—Em, eV; SEY(4)—yield ratio δm ; SEY(5)—Emission energy, eV; SEY(6)— α(θ); SEY(7)—Electron Absorbing plane, mm;

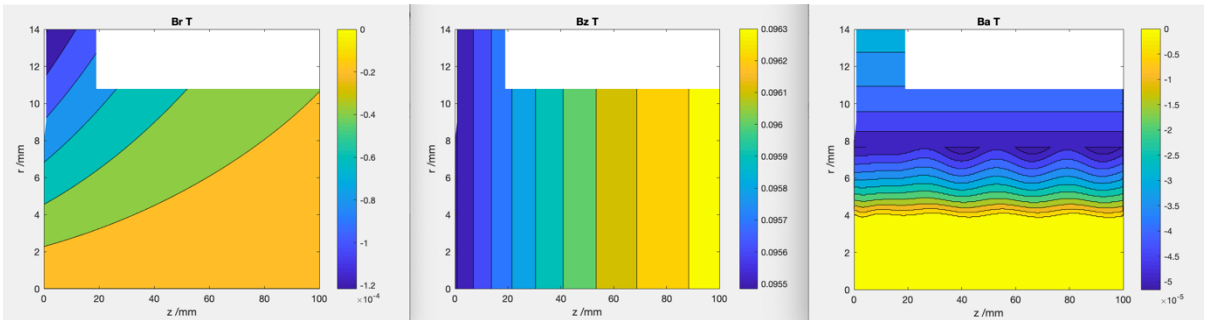
$$\frac{I_{ts}/I_0}{\delta_m \alpha(\theta)} = \begin{cases} \left(\frac{E_0 - E_s}{E_m \alpha(\theta) - E_s} e^{1-\frac{E_0-E_s}{E_m\alpha(\theta)-E_s}}\right)^{0.56}, 0 < \frac{E_0 - E_s}{E_m \alpha(\theta) - E_s} < 1 \\ \left(\frac{E_0 - E_s}{E_m \alpha(\theta) - E_s} e^{1-\frac{E_0-E_s}{E_m\alpha(\theta)-E_s}}\right)^{0.25}, 0 < \frac{E_0 - E_s}{E_m \alpha(\theta) - E_s} < 3.6 \\ 1.125\left(\frac{E_0 - E_s}{E_m \alpha(\theta) - E_s}\right)^{-0.35}, \frac{E_0 - E_s}{E_m \alpha(\theta) - E_s} > 3.6 \\ 0, \frac{E_0 - E_s}{E_m \alpha(\theta) - E_s} < 0 \end{cases}$$

SEY(8) to SEY(11) is for split line for thermal loading analysis when they are available, the line will be defined by z1=SEY(8) mm, r1=SEY(9) mm, z2=SEY(10) mm, r2=SEY(11) mm.
figureplotBE: figure plot ‘on’ or ‘off’ for final optics results.

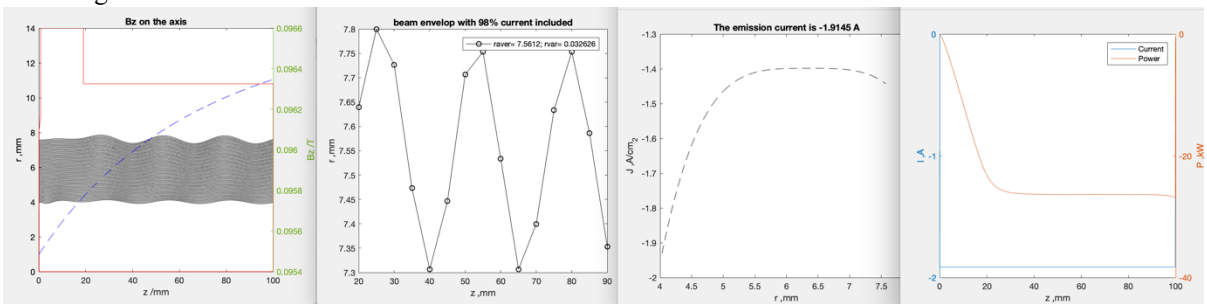
For the above example, the graphical output is shown below,



Final electro-static results



Final magneto-static results



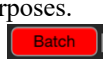
Final optic results,

Other example input files for optics simulations are also provided in the library with the software, which includes:

1. GUN_FCCTSMBK_full_80kV.txt for FCC TS MBK, gun plus transmission section
2. GUN_FCCTSMBK_collector_80kV_RF_v3.txt for collector of FCC TS MBK
3. GUN_LHC.txt for whole optics design of LHC HE Klystron
4. GUN_36GHzHOMMBK.txt for whole optics design of 36GHz HOM MBK
5. GUN_SLACX50MW.txt for whole optics design of X-band 50MW Klystron
6. GUN_220GHzBWO.txt for gun design of 220GHz FW BWO
7. GUN_140GHzTWT.txt for whole optics design of 140GHz FW TWT

III. Batch files

Apart from single magnetic and optics simulations, another useful functionality is batch simulations for parameter sweep or optimization purposes.

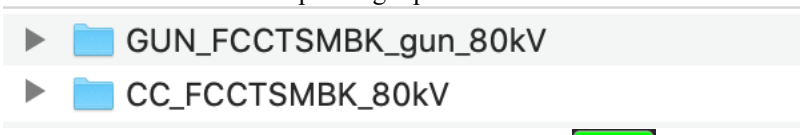
By pressing Batch button 

, another text file is supposed to be opened to determine which input files should be run in which order, an example of the contents of such a text file (Batch_task_example.txt) is shown below,

```
tasks  2
MAG  CC_FCCTSMBK_80kV.txt
TRK  GUN_FCCTSMBK_gun_80kV.txt
```

In the first line, following the keyword ‘tasks’, the number ‘2’ indicates how many tasks will be executed.
From the 2nd line forward, those tasks will be executed one by one, if the keyword is ‘MAG’, then the magneto-static module will be launched, while if the keyword is ‘TRK’, then the optics module will be launched. After that the indicated file with the file name after the keyword will be found and executed directly; Notice that the box 

will be automatically ticked, meaning that the simulation will be launched without selecting the input files manually. Another issue to keep in mind is that all the input files supposed to be run in the batch mode should be put into the same folder where the batch text file is located.
For each individual simulation in a batch run, the graphical results will all be saved as .jpg files in the sub-folder with the same name as the corresponding input file.



When the batch simulation finishes, the green button 

will turn back to red.

It is worth to mention that the box 

could be manually ticked in normal magneto-static or optics simulations, in order to activate the automatic input file reading. In this case, the present active input files (for example, those recently opened/executed) will be run directly instead of selecting them by hand.

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