BuildCavity

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Abstract

BuildCavity is a graphic interface to SUPERFISH for the study of superconducting cavities of elliptical shape. The code allows changing interactively the program geometry on the screen, executing SUPERFISH and tuning the cavity by iterating through a series of SUPERFISH runs.

The geometrical and electromagnetic parameters of the cavities can be stored in a database for analysis of the dependence of the cavity performance with respect to the geometrical parameters. Separate tuning routines for the end groups are available and a multicell cavity can be assembled and analyzed automatically from the cells in the database.

Contents

1 Distribution and program requirements **1**

2 Current Version **1**
2.1 Modules of the code 1

3 How to run the code **3**

4 Errors **3**

5 Background **3**
5.1 Requirements on cavity performances (e.m. and mechanical) . . 3
5.2 Geometrical parametrization of the cell shape 3

6 Internal cells, end cells, end groups and cavities **4**
6.1 The half-cells 4
6.2 The end group 4

7 First execution **4**
7.1 File option 5
7.2 Help 5
7.3 HC var parameters 5
7.4 Superfish Path 5

8 The main BuildCavity window **6**
8.1 Details of the main window 6
8.2 Geometrical parametrization of the cell shape 11

9 The Cavity Database window **12**

10 The End Group window **13**
10.1 The End Group Database 16

11 The Build MultiCell window **16**

12 Mechanical analysis of the cavities **18**

List of Figures

1 A multi-cell cavity and its building blocks 4
2 File Option 5
3 Material Properties 5
4 Help 5
5 Main Window 6
6 Main Window Run 7
7 Geometric Parameters 8
8 Physical Parameters 8
9 Tune Window 10
10 Help button 10
11 Cavity Shape parametrization used for the definition of the half-cell shape 11
12 Cavity database interface 12
13 End Group Window 15
14 Tube length defintions 15
15 End group Database 17
16 Multicell Window 18
17 Cavity Output Window 19
18 Cavity Output Window Completed 19
19 Summary output printed by BuildCavity 20

List of Tables

1 Structure of Cavity Database Table 13
2 Structure of EndGroup Database Table 14

1 Distribution and program requirements

The code is distributed as python source code, via remote repository.

BuildCavity runs on PC running Windows, it is written in Python and is distributed in the form of python scripts. It is sufficient to download all the files contained in the repository folder and compile the main script "BuildCav2.py" through the prompt window (see section 3). In the future, it will be distributed in the form of an executable file and a necessary folder. It will be sufficient to create a connection to the executable file and copy the folder to make it works.

No electromagnetic calculation is actually performed by BuildCavity itself, all the cavity computing is performed by SUPERFISH. BuildCavity prepares, through python lines of codes and instructions, the SUPERFISH input files and saves the SUPERFISH outputs in order to use the simulated cavity data. The latest version of BuildCavity uses the 7.16 SUPERFISH version. It is necessary to have SUPERFISH installed on the pc. For details on SUPERFISH or for instructions on download, please refer to the Los Alamos site (`http://laacg1.lanl.gov/`).

It works with the most recent version of Python **3.12.4** and of Numpy **2.0.0**.

2 Current Version

The current program version is 2.1. All the scripts are accessible from the remote repository `https://baltig.infn.it/applications/buildcavity`, where the latest versions are promptly updated. Alternatively, all the code is available in a private repository on github (`https://github.com/elisadelcore?tab=repositories`) but the access should be requested.

2.1 Modules of the code

In this subsection you can find a brief description of the code structure and its modules.

1 The main script to run to open the GUI is **BuildCav2.py**. Here are listed all the functions that define something acting directly on the GUI (i.e. read of the cells parameters, fill of the electromagnetic parameters obtained during a SuperFish run, etc);

2 **cavityOutput.py**: defines the actions required for the multicell output window (see Fig. 17):

- plot the transit time factor based on betamin and betamax defined by the user and retrieve the effective beta
- plot the field data and compute the field flatness

- replot the cavity profile
- after the TTF computation, enable the print button to show the summary of the simulations

3 db_cavity.py: defines the actions required for the half cell database;

4 draw.py: defines the function for the drawing of the cell/cavity profile;

5 Draw_cavity_profile.py: defines the function for the drawing of the cell/-cavity profile;

- Defines the coordinate used to plot the profile of HC, EG or multicell
- Check continuity between iris radius dimensions
- circ_arc and ellipse_arc are used for the multicell geometry profile design

6 electromagnetic_functions.py: functions defining the resonance frequency and the beta;

7 EndCell.py: defines the database actions to retrieve the end cell data and fill the parameters on the end group window;

8 endGroupDb.py: defines the database actions to retrieve the end group data from the database;

9 geometry.py: defines the functions to compute the geometry of the cavity:

- Conversion from geometric to physics parameters
- Conversion from physics to geometric parameters
- Definition of ellipses tangent points
- Calculation of the slope of the tangent line to an ellipse passing through a point and the point of tangency
- Calculation of the points of intersection between a line and an ellipse

10 info_Tube.py: opens a window containing the information about the tube lenghts definitions;

11 InnerCell.py: defines the database actions to retrieve the pen cell data and fill the parameters on the end group window;

12 Mat_Prop.py: defines the material properties you can find in the File option;

13 paramDef.py: opens a window containing the definitions of the geometric and physic parameters;

14 Press_Button_ELMG_simulations.py: contains the main electromagnetic functions used;

15 printt.py: contains the function to show the summary of the simulations;

16 Tune_parameters.py: opens a window for the definition of the tuning accuracy.

3 How to run the code

The code must be started via the command prompt. First, you need to navigate to the project folder:

```
cd "path/of/the/folder"
```

You need to run the main script of the program ('BuildCav2.py'):

```
python BuildCav2.py
```

Then, the main GUI will open and you can start the cavity design.

4 Errors

If during the execution you get some errors, you should open the GUI from the prompt and not by double clicking on the exe file. In this way you can read the error shown in the prompt interface.

5 Background

First of all, a few words about the motivations that underlie this work. In our laboratory, we have been working on the design of elliptical shaped low beta cavities since a few years.

5.1 Requirements on cavity performances (e.m. and mechanical)

The operational requirements of superconducting cavities impose limits on the electric and magnetic fields on the cavity surface. Therefore, it is necessary for the cavities to be designed with low values of the peak field ratio with respect to the accelerating field from an electromagnetic standpoint.

Another consideration in the design of reduced beta cavities is their inferior mechanical stability when compared to electron cavities. Since this aspect is also influenced by cavity geometry, it must be considered in the design process.

The mechanical and electromagnetic parameters of the cavity depend significantly on its shape. Hence, a suitable description of the cavity geometry is necessary to minimize the impact of individual geometric parameters on cavity performance. Ideally, one would aim for a parametrization allowing variation of a single geometric parameter to modify a specific electromagnetic or mechanical characteristic of the cavity while keeping all others factors constant.

5.2 Geometrical parametrization of the cell shape

In the past, people have realized that the aspect ratio of the iris ellipse is an independent parameter that can be used to minimize the peak electric field in

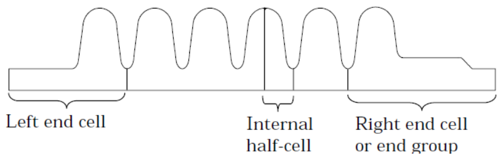

Figure 1: A multi-cell cavity and its building blocks

the iris region, without requiring any other modifications to the electromagnetic behavior of the cavity.

To further develop this concept, we have created a parametrization of the cavity shape that considers many electromagnetic and mechanical aspects of cavity performance.

BuildCavity is our tool for investigating the electromagnetic cavity parameters in relation to its shape. Additional tools are available for exploring the mechanical behavior of the cavity, and will be integrated into future versions of BuildCavity.

6 Internal cells, end cells, end groups and cavities

For the sake of simplicity, I will define the key elements needed to build a multi-cell cavity with BuildCavity: the internal half-cells, the end-cells and the end groups.
A typical multi-cell cavity and its building elements are shown in Figure 1:

6.1 The half-cells

This is the geometry of all the half cells (inner, pen and end cells).

6.2 The end group

In this case, by choosing the desired designed pen and end cells, and by defining properly the beam tubes lengths, the geometry of the end-group is realized.

7 First execution

The first thing to do when the program is opened, is to define a new project or to open an existing one. See the following section.

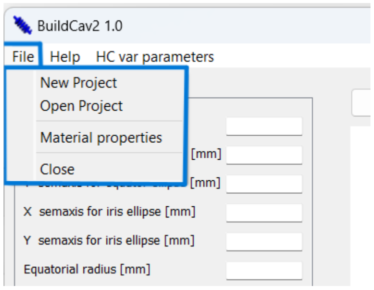

Figure 2: File Option

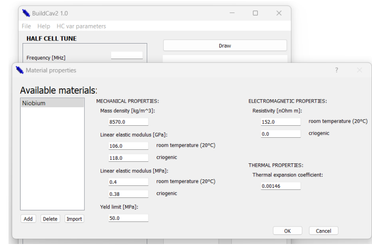

Figure 3: Material Properties

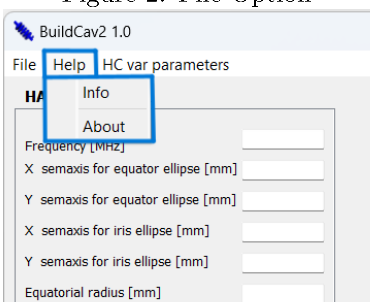

Figure 4: Help

7.1 File option

As a first step, it is required to define a **new project** or **open** an existing one, from the file option in the main window. Please pay attention to the name of your folder: you can't have empty spaces in the folder name or in any folder names belonging to the path of your project location.
The material properties button displays the mechanical, electromagnetic and thermal properties of Niobium.

7.2 Help

The help tab just gives you some info about the developed project (**About**) and redirects you to this guide pdf (**Info**).

7.3 HC var parameters

Not yet implemented.

7.4 Superfish Path

When you run SuperFish for the first time, a specific folder named 'elmg_file' will be created in the directory of your project. All the electromagnetic simulations outputs will be saved at this path.

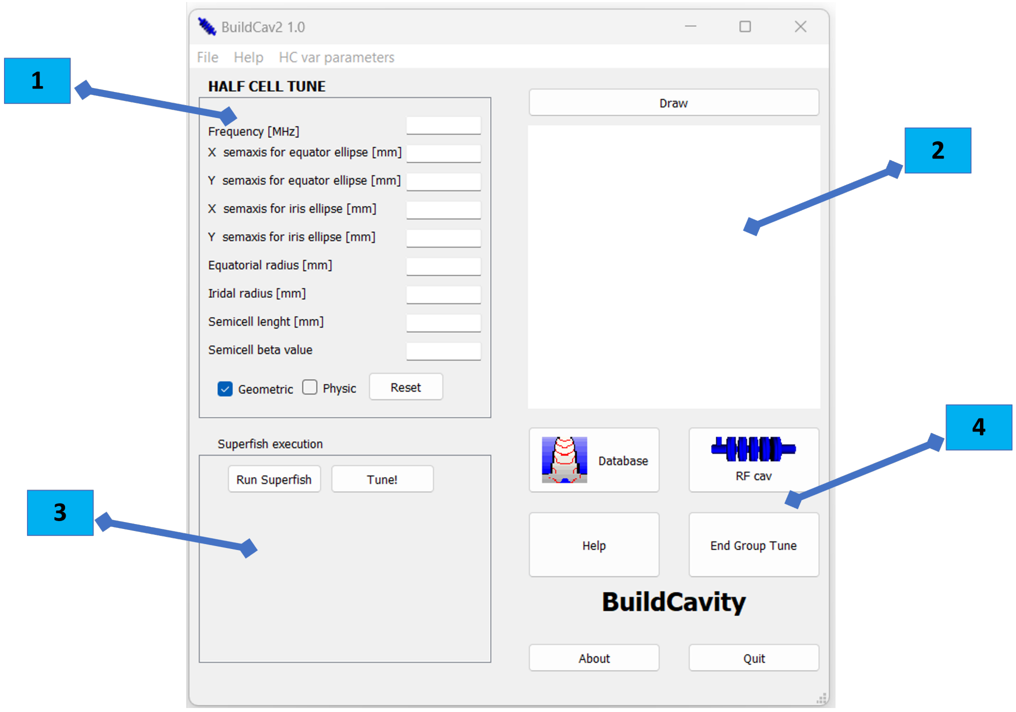

Figure 5: Main Window

BuildCavity now works with the most recent version release (Version 7.16) of SUPERFISH and does not work with previous versions due to changes in SUPERFISH outputs file structures.

8 The main BuildCavity window

This is the main window of the designed program. Beyond the upper line of tabs already explained (see sections 7.1, 7.2 and 7.3), on the left side of the window there is the half cell design region. After choosing the type of parameters (geometric or physical), each cell should be filled with the desired value. The **reset** button allows to clear all the cells.

Anyway, to give a more detailed description of this window, please refer to the following subsection.

8.1 Details of the main window

The window is divided into 4 regions:

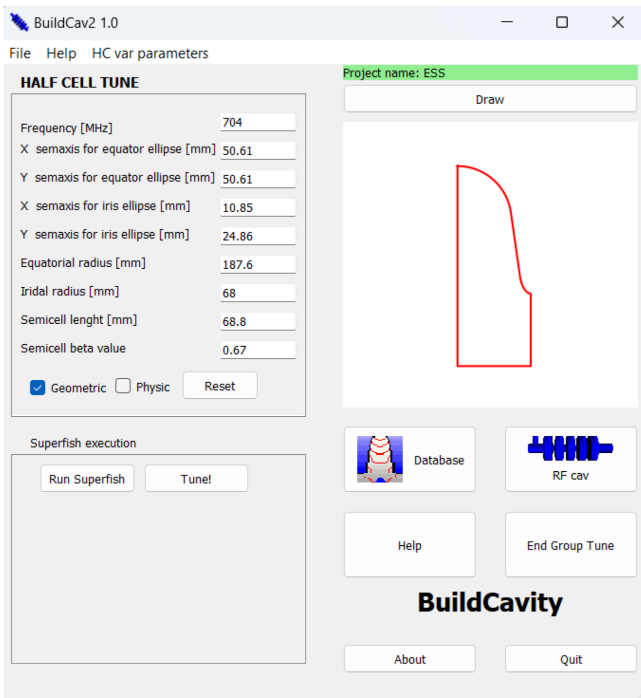

Figure 6: Main Window Run

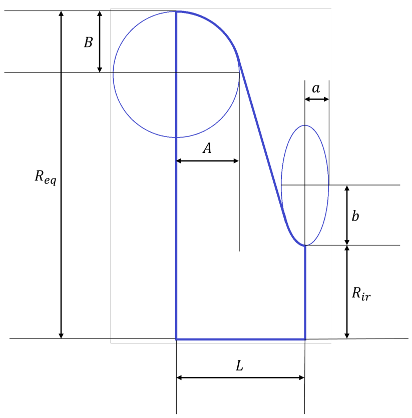

Figure 7: Geometric Parameters

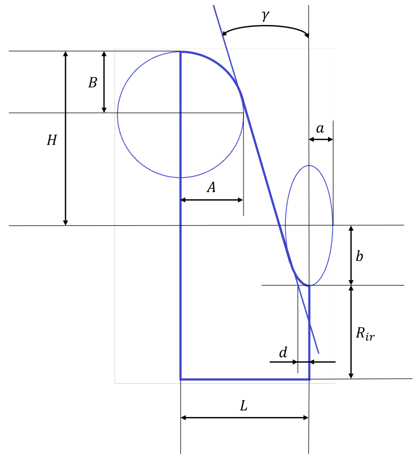

Figure 8: Physical Parameters

1 The *Cavity Geometrical Parameters* area is where the geometrical parameters of the cavity are input. The needed parameters, if you choose the physic parameters are: the cavity frequency (MHz), the iris radius (mm), the wall angle (degrees), the aspect ratio R and r of the equator and the iris, respectively, the wall distance d (mm), the half cell length (mm) and an estimate of the distance between the ellipse centers. If you choose the geometric parameters, you need to enter: the cavity frequency (MHz), the x and y semaxis for the equator ellipse (mm), the x and y semaxis for the iris ellipse (mm), the equatorial radius (mm), the iridal radius (mm) and the half cell length (mm). A last input box allows you to specify the desired cavity beta value (that is used in the SFO calculation). In Figure 7 and 8 are shown the two sets of parameters.

2 As the user enters the values for the geometrical parameters of the cavity, it is possible to plot the corresponding profile in this area.

3 This area is devoted to the cavity analysis or tuning through SUPERFISH. The **Run Superfish** button allows running a single instance of SUPERFISH on the cavity geometry and displaying the summary results. In this case, the frequency that has been specified in the input box is only used as the SUPERFISH starting frequency.
The **Tune!** button allows to start the cavity tuning process. An iterated SUPERFISH execution is performed, varying the cavity geometry according to the Slater coefficients reported by SUPERFISH until convergence to the desired frequency is reached. In order to perform the cavity tuning BuildCavity asks the desired tuning accuracy to use.

When one of the two SUPERFISH control buttons is launched, all the outputs of the simulations will be saved in a subfolder of the project directory. Note: if you want to use all the data of the SUPERFISH run, you can access them from the files stored in the working directory. You can use these files.

In order to determine the cell-to-cell coupling, when the cavity is being tuned, the last SUPERFISH simulation is performed with the proper boundary condition for the zero mode of the infinitely periodic structure. The cell-to-cell coupling is evaluated from

$$k = \frac{f_\pi - f_0}{(f_\pi + f_0)/2} \tag{1}$$

The inner cell tuning is controlled by the dF/dR Slater perturbation coefficient at the equator.

4 In this area four buttons allow to design end groups and multicell cavities, and interact with the cavity database.

The **Cavity Database** button allows managing the database table of half cells. After tuning a half-cell the database can be accessed and the cavity can be stored within it. Directly pressing this button after the program starts, allows retrieving a geometry from the database.

The **RF cav** button allows displaying the Build Multicell window, described in the section 11. From this window, a multicell cavity can be assembled from the internal cells and end groups stored in the database.

The **End Group Tune** button allows to design the end group by choosing the cells and the tubes you want. In this case the parameters of both the cells can be varied. The tuning is obtained varying the diameter of the whole end cell of the cavity. This window will be described deeply in the section 10.

The **Help** button shows you 2 images related to the definition of what physic and geometric parameters are (Figure 10). Please refer to section 8.2 for further information.

The **About** button gives you some information about the developed software.

Finally, the **Quit** button lets you close the graphic interface.

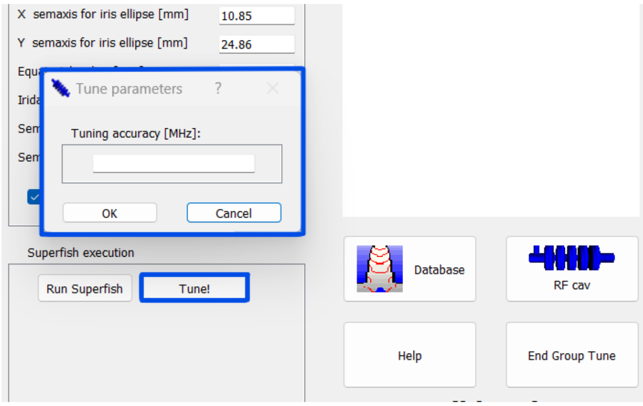

Figure 9: Tune Window

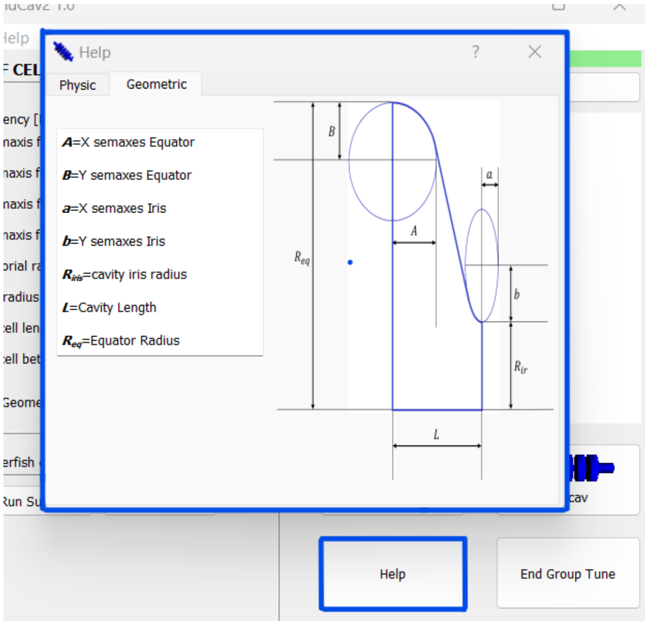

Figure 10: Help button

8.2 Geometrical parametrization of the cell shape

In the past, people have realized that the aspect ratio of the iris ellipse is an independent parameter than can be used to minimize the peak electric field in the iris region, without any other modification to the electromagnetic behavior of the cavity.

To extend this concept we developed a geoemtry parametrization of the cavity shape that takes into account many electromagnetic and mechanical aspects of the cavity.

BuildCavity is our tool for the investigation of the electromagnetic cavity parameters as a function of its shape. Other tools allow the investigation of the mechanical behavior of the cavity, and will be integrated in the future versions of BuildCavity.

The description of the half-cell uses the following parameters, schematically shown in Figure 11. It includes both the physical and geometric parameters definitions.

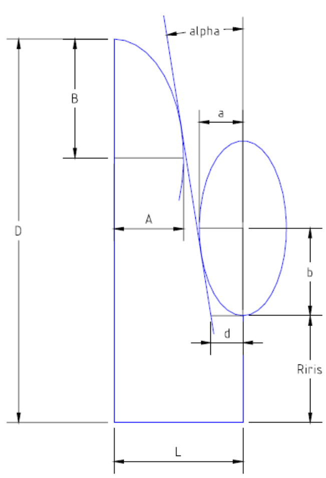

Figure 11: Cavity Shape parametrization used for the definition of the half-cell shape

L is the half-cell length, determined by the beta and the RF wavelength through the resonance condition $L = \lambda\beta/4$.

R_{iris} is the bore radius at the cavity iris.

α is the wall angle inclination.

d is the distance of the cavity wall from the iris plane.

R+B/A is the aspect ration of the elliptical equator.

r=b/a is the aspect ratio of the elliptical iris.

H is the distance between the two ellipse centers (not shown in the figure), which is used as a tuning parameters and determines the cell radius (D=R_{iris}+b+B+H).

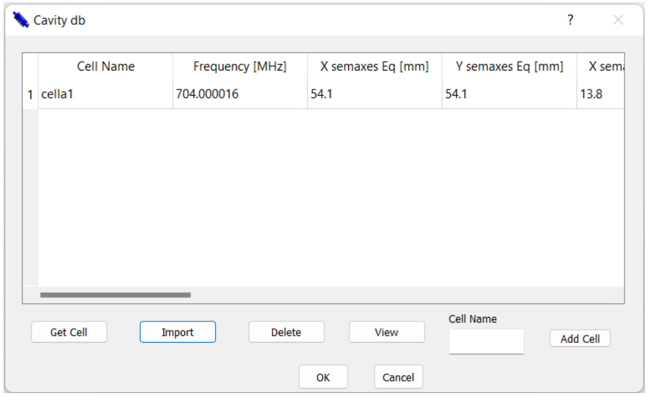

Figure 12: Cavity database interface

In our parametrization[1]. the two ellipses are defined only through their aspect ratio and we need a tuning algorithm that preserves whis aspect ratio (changing both the ellipse axes by the same amount). So, in order to stick to this choice of parameters we could easily use the available tuning codes of the SUPERFISH package, and developed a graphic interface and tuning program for the cavities.

9 The Cavity Database window

In this area the database of the desired cavity is shown. As a starting point, the window will be empty; only after the choice of a specific db to upload or the creation of a new file through the "Get Cell" button, the window will be populated. The latter button will work only after the run of a SUPERFISH simulation, because its output parameters are required for some cells.
"Delete" allows to eliminate a particulare cell or end group from the database file while "View" allows to select a specific row and to show its parameters in the main window of the program. Furthermore, if the displayed cell has to be added to the selected database file, first provide a name in the "Cell Name" section and then use "Add cell" button. All changes will be effective after the "Ok" selection, on the other hand they will not be saved in the case of "Cancel" selection.
The structure of the Cavity Database table is shown in Table 1.

Following, based on the cavity database table, the structure required for the input file is defined:

Cell Name; Frequency [MHz] ; A [mm] ; B [mm] ; a [mm] ; b [mm] ; R [mm] ; r

[1] Cavity Design Tools And Applications To The Trasco Project, P. Pierini, D. Barni, A. Bosotti, G. Ciovati, C.Pagani, in Proceedings of the Ninth Workshop on RF Superconductivity, Santa Fe, NM USA, 1-5 November 1999;

Cell Name	Frequency [MHz]	A [mm]	B [mm]	a [mm]
b [mm]	R [mm]	r [mm]	L [mm]	Geom Beta
Epeak\Eacc	Hpeak\Eacc	r\Q [Ohm]	Q BCS @ 2	K [%]

Table 1: Structure of Cavity Database Table

[mm] ; L [mm] ; Geom Beta ; EpeakEacc ; HpeakEacc ; rQ [Ohm] ; Q BCS @ 2 ; K [%]

The input file must be in .txt format.

All the half cells data stored in the database file of your project will be shown.

Options :

Add to db After entering the name to be used to define the cell in the 'End Group Name' cell, by clicking on this button you add a new row to your table with the latest computed data.

Import It allows to select a different file to use as database source file.

Delete By selecting an entire row or just a cell, the corresponding row will be deleted. The actionwill take effect only after clicking on **OK**.

View By selecting an entire row or just a cell, the corresponding row will be displayed in the end group window. The action will take effect only after clicking on **OK**.

10 The End Group window

The structure of the End group window is shown in Figure 13 .
As in the Main Window, the left part is demanded to the geometrical design. This frame is split into two columns. The leftmost one refers to the pen cell, while the other one refers to the end cell. The values for the pen cell and the end cell profiles need to be uploaded using the **Pen Cell** and the **End Cell** buttons. These allow to recall the half cell stored values of the project and lets you choose the set of data for both the cells. Again, before the upload, it is necessary to choose the type of parameters you want to use for the design (geometric or physic).

Then you have to set the length of the tubes. 'Tube length' is the total length of the beam tube in mm; 'Tube length@Riris' is used when the iris radius of the last iris is greater than the iris radius of the internal cell. In this case, this is the length of the tube to be kept at the larger radius. A 45-degree transition is then made to the internal cell iris radius. If this value is zero or if the values of the iris radii and beam length are inconsistent between themselves, the

EG Name	Frequency [MHz]	Geom Beta	Epeak\Eacc	Hpeak\Eacc
r\Q [Ohm]	Q BCS @ 2	k [%]	PC A [mm]	PC B [mm]
PC [mm]	PC b [mm]	PC R [mm]	PC r [mm]	PC L [mm]
EC A [mm]	EC B [mm]	EC a [mm]	EC b [mm]	EC R [mm]
EC r [mm]	EC L [mm]	L Tube [mm]	L Tube@Riris [mm]	

Table 2: Structure of EndGroup Database Table

code defaults to keeping the end half-cell iris radius all over the value provided in the 'Tube length' box. If you want to keep the whole tube radius at the value of the end iris please set this value to zero (Figure 14). By clicking on the question mark, it's possible to retrieve the definitions related to these two labels.

Alternatively, you can upload from the **Database** button, the values of a previously stored end group.

Once you have compiled all the fields, you can start the electromagnetic simulations by clicking on the **Run Superfish** button. All the outputs will be saved in the 'elmg_file' subfolder of your project directory. Then you can tune the cavity (**Tune!** button); in this case you have to choose the method of tuning: tuning with the alpha parameter or with the equator radius.

In the case where on the main coupler side a bigger beam tube is required in order to provide the power coupling, for the lowest beta cavities the perturbation introduced by the tube may lead to a big variation of the wall angle to recover the desired frequency. Ths may influence the behavior of the cavity under Lorentz forces, for the case of pulsed operation. In this case it could be more effective to use an additional half-cell die and rely on the big "Slater Coefficient" of the cell at the equator to perform the cavity tuning.
The code output of the Superfish executions will be displayed in this area.

Be sure to save the cell in the database if you are satisfied with its performances and you want to build a multicell cavity with it.

The database file is unique, all the data saved about half cells, end groups or multicells are stored there. Each row contains a label to filter the type of data.

The structure of the EndGroup Database table is shown in Table 2.
In the following lines, you can find the structure required for the input file.

Cell Name; Frequency [MHz] ; Geom Beta ; EpeakEacc ; HpeakEacc ; rQ

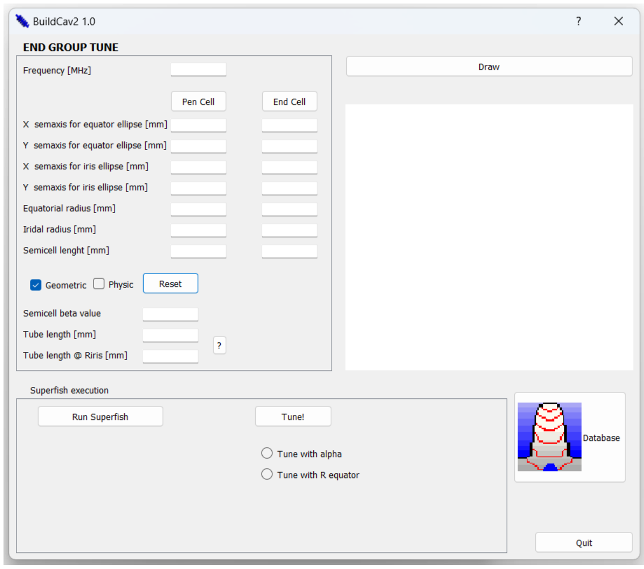

Figure 13: End Group Window

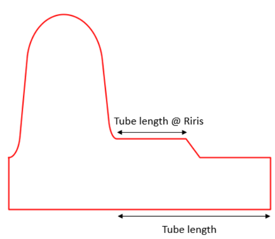

Figure 14: Tube length defintions

[Ohm] ; Q BCS @ 2 ; K [%]; PC A [mm] ; PC B [mm] ; PC a [mm] ; PC b [mm] ; PC R [mm] ; PC r [mm] ; PC L [mm] ; EC A [mm] ; EC B [mm] ; EC a [mm] ; EC b [mm]; EC R [mm] ; EC r [mm] ; EC L [mm]; L Tube [mm]; L Tube @ Riris [mm]

You can also draw the profile of the end group designed by clicking on the **Draw** button.

In reduced beta cavity, the requirement on field flatness does not imply that the internal cell and the external cell has exactly the same frequency. Thsi can be explained in a simple way. Due to the cell shortening with respect to the β=1 geometry and to the presence of the beam tube, the field lines at the last inter-cell iris have a deformed pattern with respect to the innermost irises. This reflects in the last cell having a different capacitive coupling with respect to the inner cells and hence the requirement for all cells being at exactly the same frequency ceases to hold.

A number of iterations with the multicell simulations is required to achieve the desired field flatness by slightly adjusting the end cell frequency.

10.1 The End Group Database

The End group Database window is shown in Figure 15 . All the end groups data stored in the database file of your project will be shown.

Options :

- **Add to db** After entering the name to be used to define the cell in the 'End Group Name' cell, by clicking on this button you add a new row to your table with the latest computed data.
- **Import** It allows to select a different file to use as database source file.
- **Delete** By selecting an entire row or just a cell, the corresponding row will be deleted. The actionwill take effect only after clicking on **OK**.
- **View** By selecting an entire row or just a cell, the corresponding row will be displayed in the end group window. The action will take effect only after clicking on **OK**.

11 The Build MultiCell window

The minimal requirement to build a multicell cavity is to have a database with at leas tan internal cell and either an end cell (to be used at both cavity ends)

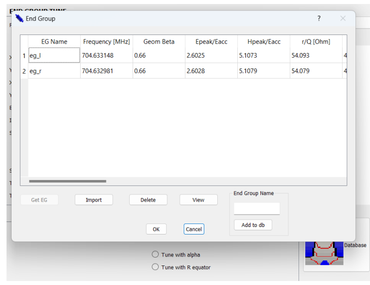

Figure 15: End group Database

or two end cells (one for the coupler side and one for the other side) or one end cell and one end group. The **Multicell** button on the Main Window can be used to load the Multicell window, show in Figure 16. The multicell database window is composed by two table: the left one referes to half cells, the right one to end groups. Using the three combox it is possible to choose the desired cells and end groups to use for the multicell construction: by clicking on the down arrow, the user can select the desired cell or end group. It is mandatory to define the number of cells. Once this has been done, it is possibile to run the SuperFish simulation by clicking on **RF cav** button: the cavity profile outputs will be shown or in the bottom of the same window or in the "Cavity Output" window (the next one) in the right bottom section.

When the SUPERFISH simulation is ended, a summary window is displayed 17. This window shws on the top left frame a summary of the output cavity parameters from the SUPERFISH run. An edit box displays the field peaks in all the cells, and the calculated field flatness from these values. The top right plot displays the on-axis field along the cavity, and the geometry is shown in the bottom left portion of the window.

Two edit boxes in teh MultiCell Output Parameters frame of the window can be used to specify the lowest and the highest beta values of the particles that need to be accelerated with the structure. Also the synchronous Phase cell must be filled. After filling these information and pressing before the **Replot** button and then the **Plot Numerical TTF curve and effective beta** button, an additional graph of the computed transit time factor curve is displayed in the bottom left part of the window. In this graph two curves are shown. The red curve is the computed TTF curve from the on-axis curve, while the blue curve is the TTF curve of a purely sinusoidal ideal cavity with an effective beta that best matches the nmerical TTF. (This effective beta can be used for beam dynamics simulations that use a purely sinusoidal cavity field). The resulting window is shown in the Figure 18.
After displaying the TTF curves, the **Print** button is actived and a summary page of the geometrical and electromagnetic parameters of both the half-cells

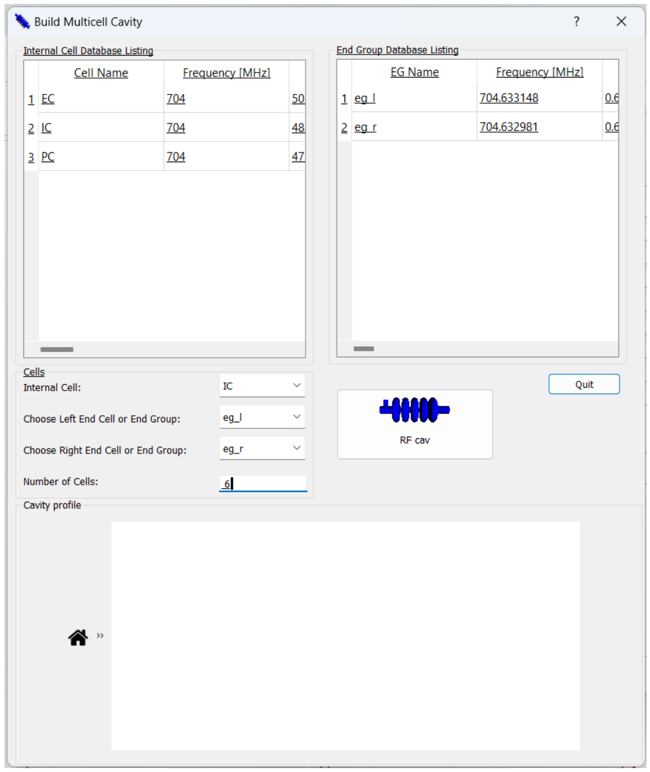

Figure 16: Multicell Window

and the multicell cavity can be printed. This summary page contains the plots in the ouput window and the relevant parameters stored in the database. An example is shown in Figure 19.

12 Mechanical analysis of the cavities

In our laboratorym BuildCavity is used in cooperation with a set of $ANSYS^{TM}$ command files and programs in order to rapidly build either from the parametrized geometry or from the SUPERFISH output a finite element model (2D axisymmetric or fully 3D) of the cells and cavities. The cavity fields of SUPERFISH can also be loaded on the FE model as radiation pressure for Lorentz force detuning calculations.

From these tools a full analysis of the mechanical properties of the cavity can be performed, including: mechanical stability under vacuum load, cavity vibrational eigenmodes (transverse and longitudinal), tuning analysis and stiffening calculations for (static) Lorentz detuning.

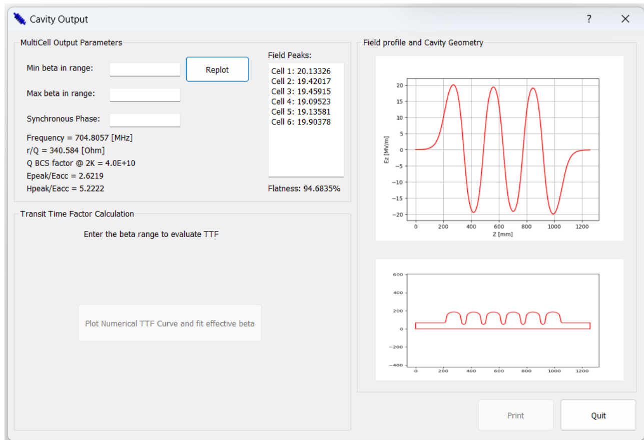

Figure 17: Cavity Output Window

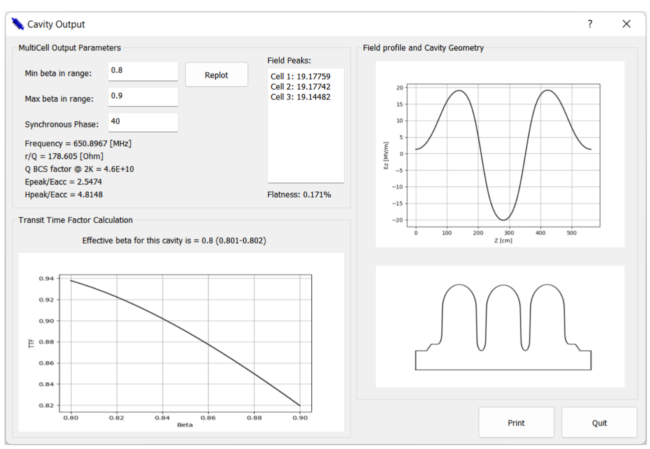

Figure 18: Cavity Output Window Completed

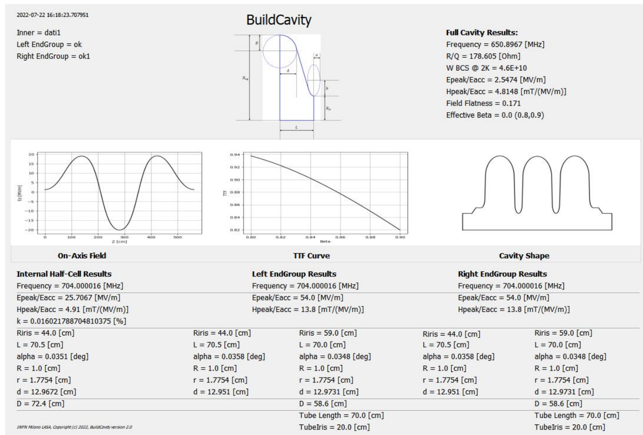

Figure 19: Summary output printed by BuildCavity

In future versions we will integrate the automatic preparation of the ANSYS models in BuildCavity.