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Electrode capacitance for RFQ vanes.

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1. Introduction

A radio frequency quadrupole is a linear accelerator which focuses (transversally), bunches and accelerates the beam with a RF electric field. The quadrupolar field distribution is achieved via four electrodes placed symmetrically around the beam axis. The geometry of the electrode tips determines the capacitance between the electrodes and hence the resonant frequency and to some extend also the power losses in the structure. In this note we report the study of the variation of the capacitance vs. the geometry of the electrodes. We have used the SUPERFISH/POISSON group of codes [1] to solve the Poisson equations around the electrodes. In section 2 we give a description of the codes used, in section 3 we describe how to use the codes in the RFQ case and in section 4 we report the results of our calculations.

2. POISSON codes

The programs we have used to do the first calculations are included in the POISSON/SUPERFISH group of codes. These were written at Los Alamos National Laboratory and consist of two set of codes, one for the design of magnets (POISSON) and another set for the design of RF-cavities (SUPERFISH). We'll use three programs in the POISSON group: AUTOMESH, LATTICE and POISSON. This codes are described in Ref.[1]:

1. AUTOMESH - prepares the input for LATTICE from geometrical data describing the problem, that is, it construct the "logical" mesh and generates (x,y) coordinate data for straight lines, arcs of circles and segments of hyperbolas.

2. LATTICE - generates an irregular triangular mesh (physical mesh) from input data for the "logical" and physical coordinates describing the problem, calculates "point charge" terms at each mesh point in regions with distributed charge density, and sets up mesh point relaxation order. LATTICE writes a binary file that is read by the equation-solving codes POISSON.

3. POISSON - solves Maxwell's electrostatic equations for the scalar potential with non linear, isotropic dielectric and electric charge distribution for two-dimensional Cartesian or three-dimensional cylindrical symmetry. It calculates the derivatives of the potential, namely the fields and their gradients, calculates the stored energy, and performs harmonic analysis of the potential. The code uses an iterative scheme that steps successively through the mesh points. Initially it was conceived to solve magnetic fields caused by electric currents and soft iron. In the electrostatic case currents are replaced by charges.

3. Description of the problem

We will present the process to estimate the capacitance of the electrodes inside an RFQ. A section of the electrodes under study can be seen in Fig.1

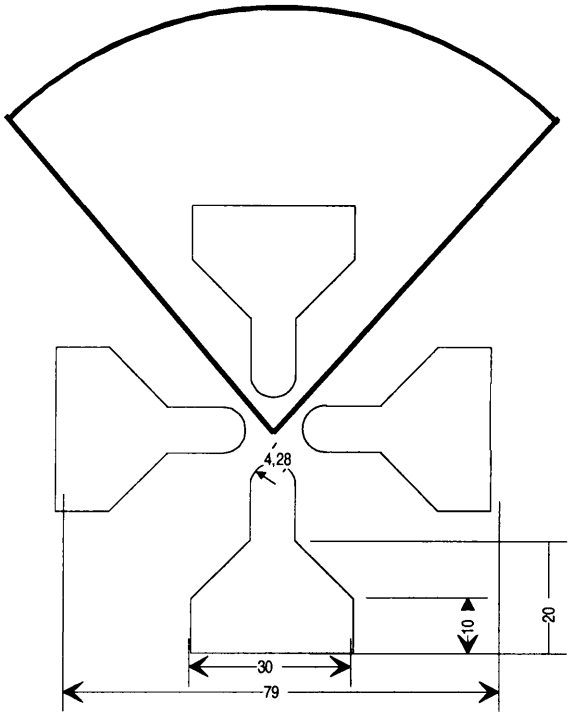


Figure 1 Section of the electrodes. Dimensions are in centimeters.

```
*RFQ WITH NOMINAL GEOMETRY.

&REG NREG=2,DX=0.2,XMIN=-
10.0,XMAX=10.0,YMIN=0.,YMAX=14.0,NPOINT=4,
 xdri=9.9, ydri=9.9,icylin=0,freq=101.28,
 YREG1=0.878, YREG2=2.95 &
&PO X=0.0 , Y=0.0  &
&PO X=-9.8994949 , Y=9.8994949  &
&PO NT=2, X0=0.0, Y0=0.0, R=14.0 , THETA=45 &
&PO X=0.0 , Y=0.0  &

&REG MAT=0,CUR=35000,IBOUND=-1,NPOINT=10 &
&PO X=1.5 , Y=3.95 &
&PO X=1.5 , Y=2.95 &
&PO X=0.428, Y=1.878 &
&PO X=0.428, Y=0.878 &
&PO NT=2, X0=0.0, Y0=0.878, R=0.428, THETA=270 &
&PO NT=2, X0=0.0, Y0=0.878, R=0.428, THETA=180 &
&PO X=-0.428, Y=1.878 &
&PO X=-1.5 , Y=2.95 &
&PO X=-1.5 , Y=3.95 &
&PO X=1.5 , Y=3.95 &
```

Figure 2 Input file for AUTOMESH. All lengths are in centimeters.

Due to symmetry, only the upper quadrant will be considered. Figure 2 shows the input describing this quadrant. The format of this input file is also extensively described in Ref.[1].
As we can observe, the problem is divided in two regions. (NREG=2)

- The first region is bordered by the bold line in Fig. 1. In the file it is represented by four points where the initial and final one coincide. We can see also element three is an arc of 45° and a radius of 14 cm. centered in the origin. By default the program will assume cylindrical symmetry around the x axis. In order to indicate there is no symmetry in this plane the variable icylin has been set to zero. The size of the mesh is determined by DX=0.2, the smaller the size, the higher the precision of the calculations and the time the program uses to do them. This size is doubled from x=0.878 and y=2.95. The parameters xdri and ydri denote the coordinates of the driving point ,i.e., where the program starts to solve the equations from.
- The second region is the electrode and is formulated in a similar way. In this region we have specified the relative voltage in Volts by input CURR=35000. The variable MAT which is the material code is set to zero. That means all point of the region are to be omitted from the problem. (There is no electric field inside a conducting material thus there is no contribution to the capacitance).

This file is ready for the POISSON/SUPERFISH codes. In addition, to indicate LATTICE to initialize the constants with POISSON default values we must put a non-blank at the beginning of the file, i.e. first row and first column. It should be noticed that two regions have to be given in the input file. This is physically explained by the fact that to describe an electrostatic problem one need at least two different surfaces at different voltages.
Once we have the input file that we've called NOMINAL.RFQ we will run AUTOMESH in the following way:

```
C:\>> AUTOMESH NOMINAL.RFQ
```

AUTOMESH gives an output ASCII file called TAPE36. In Figure 3 we see the first lines of this file. As well as the special parameters related with each triangle in the mesh, there is a list of constants (for instance *2 5 means constant 2 is set to zero). This constants have been set to the defaults for POISSON. In case these values were not appropriate, they can be modified when running LATTICE or POISSON.

```
+---------------------------------- TAPE36 ----------------------------------+
¦*RFQ WITH NOMINAL GEOMETRY.
¦C:\NOMINAL.RFQ
¦ 2-27-95  17:27
¦POISSON
¦ *2  5 *109    3090 *19  0 *21 0 1 0 0 *36    7
¦ *9  1.0000 *120 2.0000000E-01  1.7560000E-01
¦ *6 -2     1.000000 *10     0.004000 *46  2 *81  1 *101  0
¦ *42     1    0    1    1
¦ *54     0.000000     0.000000     0.000000     0.000000
¦ *30      100000 *66     1.000000 skip
¦   1  1   0.000000000     0.000000000     0  0  region
¦   51   1   0.0000000   0.0000000
¦   51   2  -0.1254286   0.1254286
¦   50   2  -0.2508571   0.2508571
¦   49   3  -0.3762857   0.3762857
¦   49   4  -0.5017143   0.5017143
¦   48   5  -0.6271429   0.6271429
¦   47   5  -0.7525714   0.7525714
```

Figure 3 TAPE36. output file of AUTOMESH

After AUTOMESH we can run LATTICE by simply typing LATTICE and keeping the default input file name. Now we have to go from a magnetic problem into an electrostatic problem. There is only a parameter that must be changed to switch between magnetostatics and electrostatics. One must set CON(66)=0.
This can be made by typing

*66 0 s

when LATTICE asks for changes in the CON values. The character 's' is typed to skip the remaining CON values. In a similar way, it's possible to change the boundary conditions if they are not correct. They are stored in the CON values 21,22,23,24.
We can see in Fig. 4 the result of the LATTICE run. The surface is divided in triangles by AUTOMESH and these are re-sized and reshaped by LATTICE to adapt them to the original boundaries of the problem. We can also see that the size of the triangles is reduces toward the tip pole of the electrode where calculations have to be more accurate.

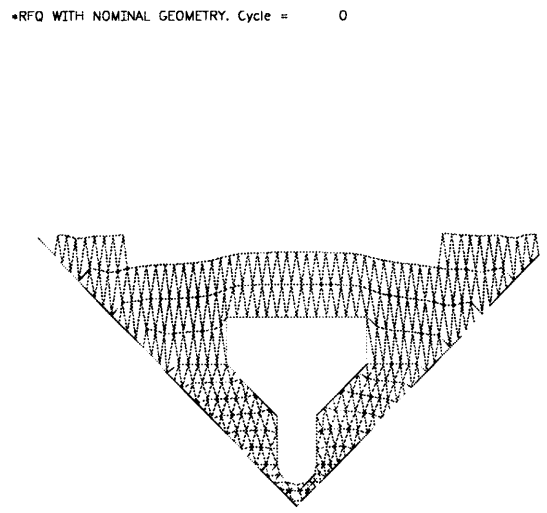


Figure 4 Output from LATTICE. The size of the mesh is reduced when approaching the higher fields to make more accurate calculations

LATTICE produces two output files called TAPE35 and OUTLAT. The former will be the POISSON input file while the latter is used for debugging purposes.
Finally, we can run POISSON. We will simply type POISSON and keep the default filenames and CON values. The program looks for a global solution of the Poisson's equations interpolating from the individual solution obtained for each mesh triangle. The equipotential lines can be appreciated in Fig. 5 The field and voltage in each meshpoint is written in TAPE35 as well as the stored energy. From this stored energy we will calculate the capacitance of the electrodes using the relation:

$$E = 1/2\ CV^2$$

where E is the stored energy, C the electrode capacitance and V is the voltage the electrode is set at.

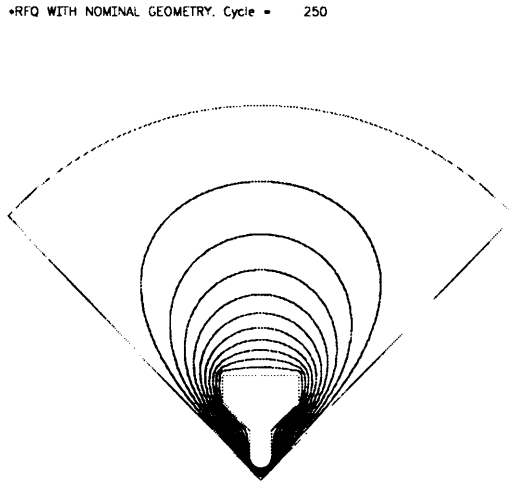


Figure 5 Output from POISSON. It shows the equipotential lines. One can see that these satisfy the boundary conditions.

Figures 5 and 6 can be obtained by typing VGAPLOT which is a graphic program that uses TAPE35 as input file
The same procedure is applicable to a general geometry. For clearness we present in the appendix a simpler example for a coaxial line.

4. Results

Following the scheme of the previous section, we have calculated the capacitance of the electrodes for different geometry. We have computed the energy stored around an electrode when the voltage reaches the maximum as shown in Fig.6.

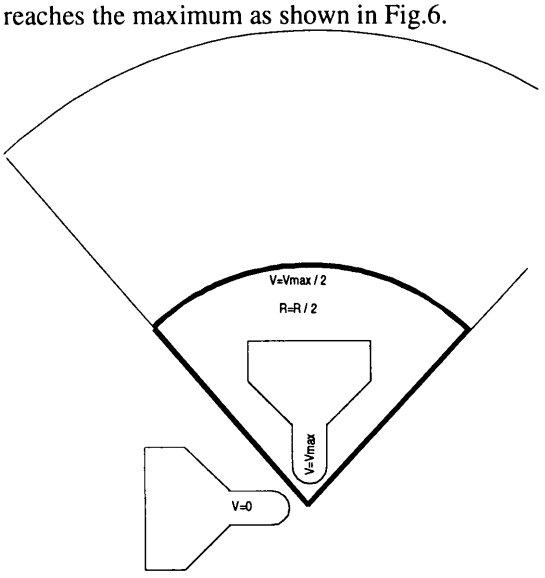


Figure 6 Assumed state for electrostatic calculations

In this conditions, the electric field between the electrodes an thus the stored energy` has a maximum. Future calculations for dissipated power and Q factor have to be averaged over a RF cycle.
We have taken the boundary conditions as to make the contour of the problem an equipotential line. Also is in this part where we find the major contribution to the capacitance
The stored energy and capacitance are calculated per unit of length (centimeter).
As the capacitance is a geometrical factor, the shape and position of the electrodes influence directly its value. We have carried out two test to get a feeling for the influence of these two factors. First, we have kept fixed the shape of the electrodes and we have changed the distance between the electrode and the beam axis. The closer the electrode to the axis, the more intense the field and so the higher the stored energy and capacitance. For the second part, we have tested the use of two different-shape electrodes. In Fig. 7 are shown the two other geometry tested which we will refer as 'reduced vanelets' and 'roundbar'. A simpler geometry will reduce the electric field outside the gap and thus the capacitance..

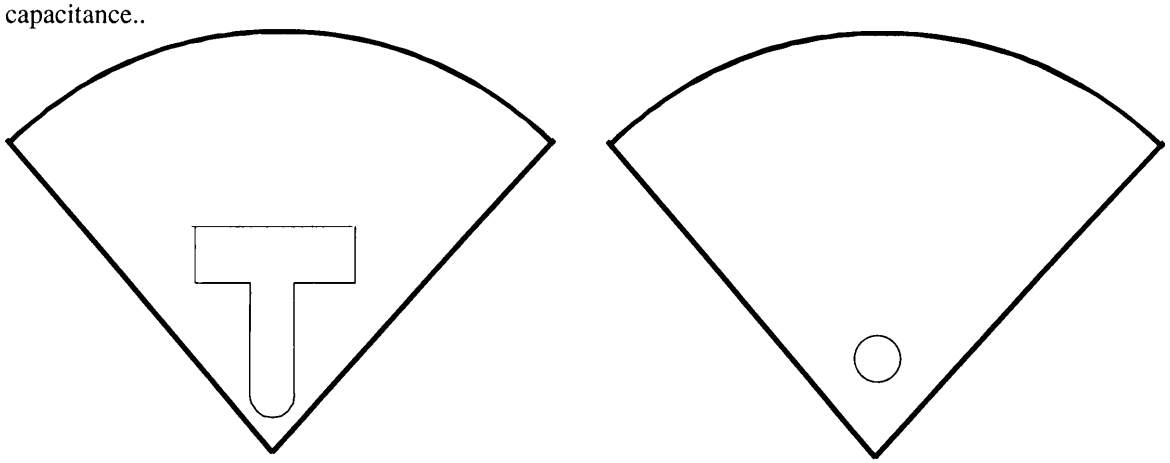


Figure 7 Different electrode shapes. Reduced vanelets and roundbar geometry

The results can be appreciated in Table 1

	Displacement (mm)	**Stored energy (J/cm)**	**Capacitance (pF/cm)**
Nominal geometry	-2	1.50 e-03	2.456
	-1.5	1.20 e-03	1.953
	-1	1.03 e-03	1.689
	-0.5	9.31 e-04	1.519
	0	**8.57 e-04**	**1.400**
	0.5	7.99 e-04	1.305
	1	7.54 e-04	1.231
	1.5	7.17 e-04	1.170
	2	6.85 e-04	1.119
Reduced vanelets	0	8.34 e-04	1.362
Roundbar	0	5.33 e-04	0.871

Table 1 Capacitance of the electrode for different positions and shapes.

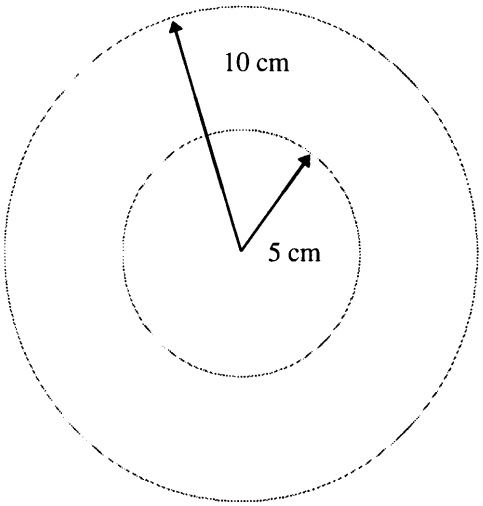
The capacitance is larger when the distance between the electrodes is decreased. This would make the dissipated power smaller but also modifies the maximum electric field which is directly related with the acceleration performance. The use of a roundbar electrode would allow a decrease of the dissipated power without affecting drastically the beam dynamics.

5. References

[1] Los Alamos Accelerator code group "Reference Manual for the POISSON/SUPERFISH Group of Codes." LA-UR-87-126 January 1987

APPENDIX: A coaxial line

As a simple case, we have taken a coaxial capacitor whose inner conductor has a radius half the outer one. The voltage between the two is 35 KV. The following pictures show the layout of the line and the input file written for this example. We remind that it is necessary to divide the problem into two closed regions. The first one represents the outer line and is built with two semicircles of radius 10 cm. The second one is also built with two semicircles with half this radius. The voltage to which the inner region is set is specified by setting the variable CURR to 35000 volts.

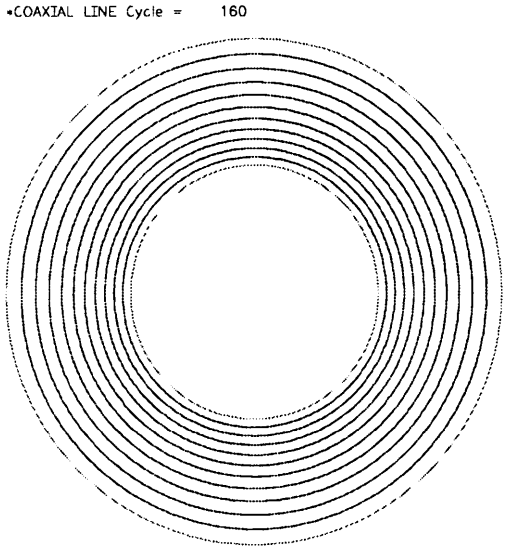



```
*COAXIAL LINE
 &REG NREG=2,DX=0.4,XMIN=-
10.0,XMAX=10.0,YMIN=-10.0,YMAX=10.0,NPOINT=3,
xdri=28.0, ydri=0.0,icylin=0,freq=101.28 &
 &PO X=10.0 ,Y=0.0  &
 &PO NT=2, X0=0.0, Y0=0.0, R=10.0 , THETA=180 &
 &PO NT=2, X0=0.0, Y0=0.0, R=10.0 , THETA=0 &

 &REG MAT=0, CUR=35000., IBOUND=-1, NPOINT=3
&
 &PO X=5.0 ,Y=0.0  &
 &PO NT=2, X0=0.0, Y0=0.0, R=5.0 , THETA=180 &
 &PO NT=2, X0=0.0, Y0=0.0, R=5.0 , THETA=0 &
```

When running LATTICE we have to input the next line when the program ask for CON values:
.....*66 0 *21 0 0 0 0 s.....
The CON value number 66 is set to zero to specify that it is is a electrostatic problem. The CON values 21 to 24 contain the boundary conditions of the bottom, top, left and right limits. Zero refers to conductor boundary conditions
The equipotencial lines calculated by POISSON can be seen below. In the output file of POISSON named OUTPOI we find the stored energy calculated by the program.

.....Stored energy = 4.9162E-04 Joules/cm.....



From the stored energy we calculate the capacitance as:

$C = 2\,E_{stored} / V^2$

which gives us a capacitance of 80.26 pF. When compared with the theoretical value obtained by the formula:

$C = 2\pi\varepsilon 0L / \log(r_1 / r_2)$

gives us the same value.