CW RFQ DESIGNING USING THE LIDOS.RFQ CODES

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New criteria arise when high-current CW linacs are considered. The main requirements for such linacs are beam acceleration with very low beam losses and reduced intervane voltage. In such cases the traditional algorithms can lead to undesired versions of the RFQ.

New concepts for parameter choices based on optimization methods and scientific visualization of space charge-dominated beam are incorporated in the new multilevel codes RFQ.3L [1].

This new RFQ code package gives users the possibility to proceed successfully from input data up to accelerating-focusing channel design and space-charge-dominated (SCD) beam simulation. There are two main features: a maximum of scientific visualization for each calculation step and the possibility to cut off undesired linac versions long before the time-consuming calculations start. The package contains codes with three levels of mathematical model complexity.

The first-level codes make only a preliminary choice of the main parameter arrays on the basis of a simplified physical model. These codes are richly supplied with visual information, which helps to quickly find the best linac version.

The second-level codes are used for channel data calculations with the real shape of the RFQ vanes. Information from the first level codes is used as input data.

The third-level codes are based on information from the first and second level codes and on complex PIC-models that are needed for a correct beam simulation in the chosen channel version.

In the case of the IPHI high-current CW RFQ, radiation purity (minimum of lost particles) and reduced intervane voltage are considered as the main optimization criteria**.**

RFQ.3L codes have been used to find the region of RFQ parameter space most likely to satisfy the design requirements. The process is fast because the beam simulation is used only for the final RFQ version. RFQ.3L gives an user intellectual advises and helps him to come to the best RFQ version by the shortest way.

The first level stage the channel, data must be chosen in a way that beam transmission can be as large as possible. The periods of vane modulation are calculated at the second stage taking into account the "ideal" vane shape (2 terms potential) and nonlinear space charge forces. The functions $U(n)$, $m(n)$, $\varphi_s(n)$ and $R(n)$ obtained at the first stage are used as input data. The third level codes LIDOS.PIC are used for beam simulation. Beam is represented as a set of macro-particles and Poisson equation is solved at every step with boundaries in the form of "ideal" vane shape. The amount of macro-particles is 50 000. A saved cartoon is used for the presentation of the beam transport. Phase portraits all along the RFQ are showed on cartoon's pictures, as well as plots of several beam parameters (transmission factor, rms emittance, mean longitudinal and transverse kinetic energies…). Information on lost particles, their input distribution, total lost power and maximal lost power per unit length are also obtained. Distribution of lost particles as functions of length along the RFQ, number of RFQ periods and particle energy are presented.

When the RFQ structure is chosen (first level) and primarily checked (third level), the 3D calculation of the real external electrical fields (i.e. fields from the electrodes, without the beam Coulomb field) is performed for the real form of the electrodes. On this stage the second-level codes are used. These codes calculate the distribution of the field potential for each cell in an electrostatic approach. The calculations are the solution of the Laplace equation with the relaxation method. As the field is supposed to be quadruple-symmetrical, the potential distribution is calculated only for one quarter of the whole region. As the parameters of neighbor cells (modulation, mean radius, length) are very close to each other and the fields differences in them occur to be less than the calculations accuracy, then base cells are used for the definition of the fields in the whole channel. The field in a cell is calculated as a function of two parameters: m - the electrodes modulation- and the ratio $s = R_0/L$, where L is the cell length. Cells are chosen based on those parameters and the fields $E(m_n,s_n)$, $E(m_n,s_{n+1})$, $E(m_{n+1},s_{n+1})$ are then calculated. Thereafter, the field in cells with intermediate values of m and s is calculated with a linear interpolation between the three base fields. Total number of base points is 39. The new length of the cells are calculated taking into account the efficiency of acceleration in real fields using the dependencies of $\varphi_s(n)$ and $m(n)$ defined previously.

On the last stage, the calculations of the particles dynamics is performed taking into account Coulomb forces and real shapes of the electrodes. The code

LIDOS.PIC is used for this task where the calculated real fields are used instead of the ideal fields. On this stage study of different tolerance influence (channel axis displacement, different sorts of voltage deviations) on beam dynamics are also performed.

The above code tools were used for RFQ designing in favor of IPHI Project (CEA, France) [2]. The following parameters were preset as well as some restrictions and requirements:

Accelerating Particles	protons
Input Energy	0.095 MeV
Output Energy	5 MeV
Beam Current	100 mA
Total Beam Emittance	0.15π cm·mrad
Operating Frequency	352 MHz
Peak Surface Field	< 29.5-30 MV/m
Kilpatrick Factor	< 1.6
Length	about 8 m
Beam Transmission	> 90%
Power of Lost Particles	< 1–1.5 KW

Minimum of Lost Particles with energy more than 3 MeV

A strategy was elaborated for creating a RFQ version who satisfies the conditions set above. A lot of versions were examined to create the needed channel. Following is the essence of this strategy: If the calculations show that particles capture in the accelerating regime is sufficiently high (~ 95%) then one can conclude that the regularities for the equilibrium phase φ_s variation and for the acceleration rate *UT* are defined finally. To prevent transverse particles losses in the last part of the channel (particles with high energy), it is necessary to increase the focusing strength when they achieve the first minimum of phase oscillations (first focus) and to increase the aperture of the following channel part. Besides, it is necessary to satisfy the upper limit of the field $E_r=U/R_0$. The aperture increase must be accompanied with the proportional voltage increase. The increasing of the focusing strength diminishes the size of the beam halo in the region of first focus. Simultaneously, the aperture decrease at this location leads in halo losses in a channel region where particle energy slightly differs from the input value. According to calculations and investigations there is a range where the raise of the transverse beam size due to the decreasing focusing strength is compensated by the aperture increasing. Thus we can avoid losses of high-energy particles in the last channel part. To keep the product $U{\cdot}T$ constant, we must also change the vane modulation.

The best RFQ version with constant U and R_0 was first calculated (U = 91.6 kV, R_0 = 4 mm). This version gave good transverse and longitudinal captures but leads in losses of high energy particles. In order to minimize power of lost particles the plots $U(n)$ and $R_0(n)$ were chosen and correction of $m(n)$ was made. In optimal case the mean bore was decreased from 4 to 3.6 mm and then increased up to 5 mm. Intervane voltage must be increased up to 25% from input to output. Vane modulation at the RFQ output does not exceeded 1.5. It means that bore radius is increasing not only at the cost of $R_0(n)$ increasing, but also at the cost of $m(n)$ decreasing. The chosen parameters are showed on Figs. 1-2 as functions of the period number. In Tables 1 and 2 RFQ parameters are given.

Table 1. Main RFQ Parameters

Operating Frequency	352 MHz
Length (w/o output part)	7.906 m
Electrical Length	9.28 (λ=0.85 m)
Number of Periods	267 (534 cells)
Bore Radius, mm	4 → 3.43 → 3.95
Vane Modulation	1→ 1.53
ρ/R_0	0.85
Vane Voltage, kV	91.6→ 82.4→ 114.4
Kilpatrick Factor	1.62 – 1.64

Table 2: Parameters of RFQ Parts

	W, MeV	φ_s, deg	Cell Nos	L, m
Matching Section and Shaper	0.104	-83	180	1.098
Gentle Buncher	0.72	-40	190	1.7
Acceleration	5	-35	164	5.108
Total	5		534	7.906

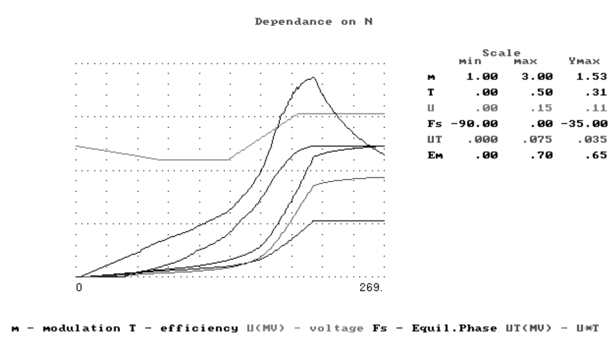

Fig.1.

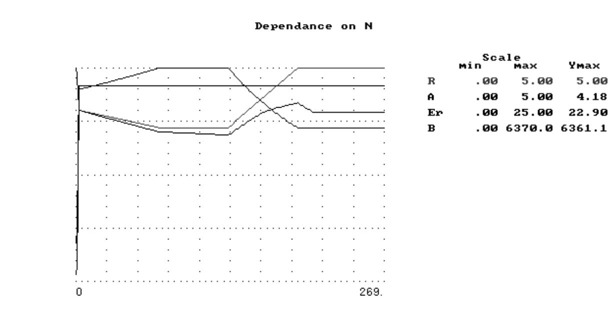

Fig.2.

The arrays of the calculated fields in the input section and in regular channel are got united. The united array is used for beam dynamics calculations We have not understood that sentence.

The results for different RFQ versions are presented below in Tables 3-5. We indicate the beam normalized emittance, *E*, the overall beam transmission, *Trans*., the accelerated particle, *Acc*., as well as the integrated power of lost particles, *P*. All results are presented for a beam current of 100 mA. The initial particles distribution is a uniform filling in the 4-dimensional ellipsoids in phase space X,X',Y,Y' with uniform distribution along the longitudinal coordinate Z and without longitudinal velocities spread. Version 0 is with constants U and R_0. Versions 1a and 1b correspond to RFQ structure with ideal RF fields (no multipoles, with images effect), 1c – with real RF fields. The next versions are presented for real RF fields and beam emittance of 0.15π cm·mrad.

Table 3

Version	• (*π·cm·mrad*)	*Trans* (%)	*Acc* (%)	*P* (kW)
0	0.1π	97.7	97.0	1.55
1a	0.1π	98.1	96.8	0.59
1b	0.15π	97.6	96.2	0.80
1c	0.15π	95.9	92.8	0.92

As it is seen from the Table 3 new version 1b with ideal fields leads practically to the same results as version 0, even for greater emittance (0.15π versus 0.1π). The comparison of versions 1b and 1c shows that in real field the overall current transmission suffer a diminution of 1.7% and a capture diminution of 3.5%. For the investigation of the influence of real fields, non-linearity in matching section on overall current transmission there was performed the calculation of the particles dynamics for the intermediate version when the real regular part was combined with ideal matching section. The difference occurs to be practically zero. One may conclude that the non-linearity of the regular channel field diminishes both the overall current transmission (95.9 versus 97.6) and the number of accelerated particles (96.8 versus 98.6). Note that the definition of the input beam parameters matching with real nonlinear channel represents itself a separate problem. When the mean square emittance $\langle xx' \rangle$ calculated in z points only slightly oscillates through z, then we have a good beam matched.

Among all calculated effects, a great interest was expressed to study the influence of a channel axis displacements on output beam parameters as well as influence of a tilt of intervane voltage. In Table 4 resume this analysis.

Version 2a – the channel axis is uniformly shifted of 0.1 mm in x and y.

Version 2b – the channel is divided in 4 sections, the ends of sections are shifted of ± 0.1 mm in *x* and *y*, and the axis represents broken line without tears.

Version 2c – the channel is divided in 4 sections, the beginning of each section is shifted on –0.1 mm in *x* and *y*, the end of each section is shifted on +0.1 mm, the channel axis has tears at sections ends.

Table 4

Version	*axis*	*Trans* (%)	*Acc* (%)	*P*
1c	ideal	95.9	92.8	0.92
2a	straight	95.5	92.6	1.05
2b	broken	95.5	92.5	1.06
2•	disrupt	93.6	90.6	2.18

As it is seen from the table, the most dangerous are the independent shifts of sections ends (no continuity of the channel).

The influence of RF fields tilts in RFQ sections on beam motion was a goal of the next series of beam simulation. There are results for the following versions:

3a - RF fields are decreased at the beginning of each of four sections by 5%, and increased at the ends by 5%; 3b – reversed for 3a, +5% then –5%; 3c - RFQ linac was considered as unique section. At the beginning of the linac, RF fields are increased by 5%, at the ends - decrease by 5%; 3d - RFQ linac was considered as unique section. At the beginning of linac RF fields are decreased by 5%, at the ends - increased by 5%. All RF variations are linear.

Table 5

Version	*Section Nos*	*RF Field*	*Trans* (%)	*Acc* (%)	*P*
1c	1	Nominal	95.9	92.8	0.92
3a	4	Increasing	93.2	90.5	2.58
3b	4	Decreasing	95.3	92.0	1.54
3c	1	Increasing	94.9	91.3	1.32
3d	1	Decreasing	96.4	93.9	0.73

As is easy to see, the RF field tilts from smaller values at the beginning of sections to larger ones at its ends decrease beam transmission in a greater extent that the opposite case. Nevertheless, the last case (version 3b) leads to a beam halo growth on longitudinal phase plane.

The third level code formally called LIDOS.PIC also implement error studies (vane voltage, misalignment and tears…). It can be used to help the designer to set the manufacturing precision and to get the expected transmission for multi errors.

REFERENCES

1. B.I.Bondarev, A.P.Durkin, S.V.Vinogradov "Multilevel Codes RFQ.3L for RFQ Designing", CAP-96, Williamsburg, Virginia, USA.

2. R.Ferdinand et al. "Optimization of RFQ Design", EPAC-98.