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Date : 29.04.2003	**RFQ 'crocodile' profile study**
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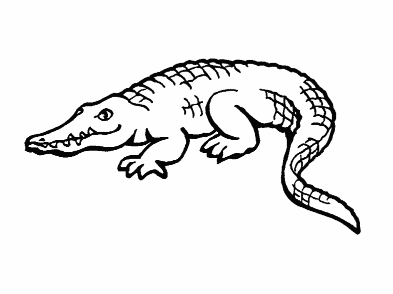
Subject : RFQ 'crocodile' transverse section profile N/RÉF. : DAPNIA_03_80	



RFQ 'crocodile' transverse section profile

Abstract :
A new concept for the 4-vanes RFQ transverse section design is introduced and tested. It consists in thickening the electrode tip, resulting in a looking like 'crocodile' profile of this region. The original benefit that was expected is to make possible the reduction of the cavity size for a given frequency. Another interest of this principle is to bring the possibility of compensating the longitudinal mean aperture variation by modifying the electrode tip geometry while keeping the outer quadrant unchanged.

This paper presents the results of tests of these two approaches applied at two resonance frequencies, 88 and 176 MHz.

Contents

1 Introduction

The main reason of the numerous efforts that are made to imagine new RFQ structures is to reduce the cavity size for a given frequency. This tendency is especially relevant for low frequency RFQs, typically lower than 200 MHz, where the commonly adopted 4 rods RFQ is now challenged by IH and 'split coaxial' structures (refer to [1]). The common principle of these structures is to make the current flux circulate longitudinally between stems that support the electrodes. Therefore the inductive component of the equivalent resonant circuit is increased, and the resonant frequency is lowered though the diameter of the cavity remains constant. In 4-vanes RFQs, the current circulation path that contributes to the inductive component L is purely transverse, so the lowering of the resonant frequency by modifying L necessarily goes with the cavity size increase.

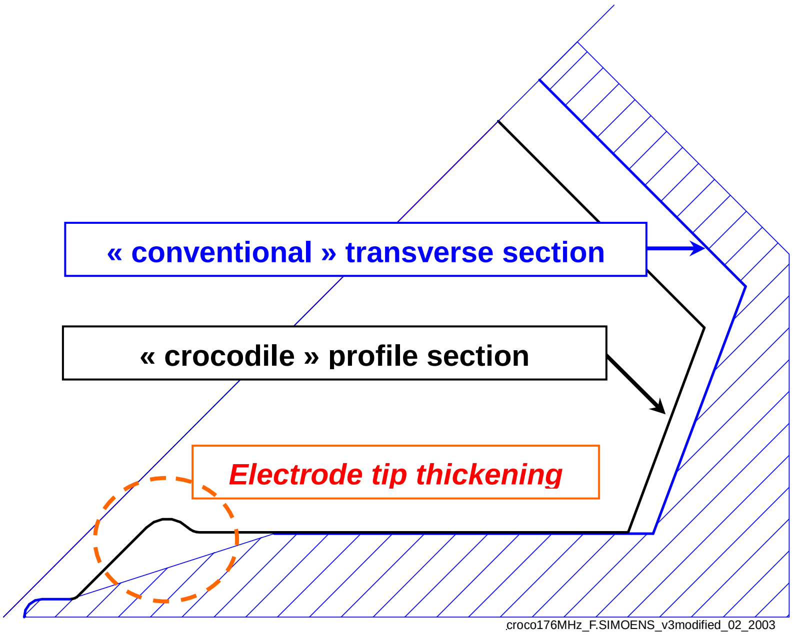


figure 1 : « crocodile profile » principle

Keeping a 4-vanes RFQ structure, we have investigated the principle of increasing the capacitive component C of the equivalent resonant circuit instead of L. This is done by thickening the electrode tip (figure 1), though keeping the extreme circular tip unchanged. The resulting profile that looks like a 'crocodile' for imaginative people is the origin of this calling (figure 2).

figure 2 : electrode tip with a 'crocodile' profile

This principle has been tested by modifying the electrode tips of two 'conventional' 4-vanes RFQ transverse sections, designed for the Spiral2 project, respectively at the frequencies 88,05 MHz and 176,1 MHz ([2]).

2 Transverse section geometrical parameters

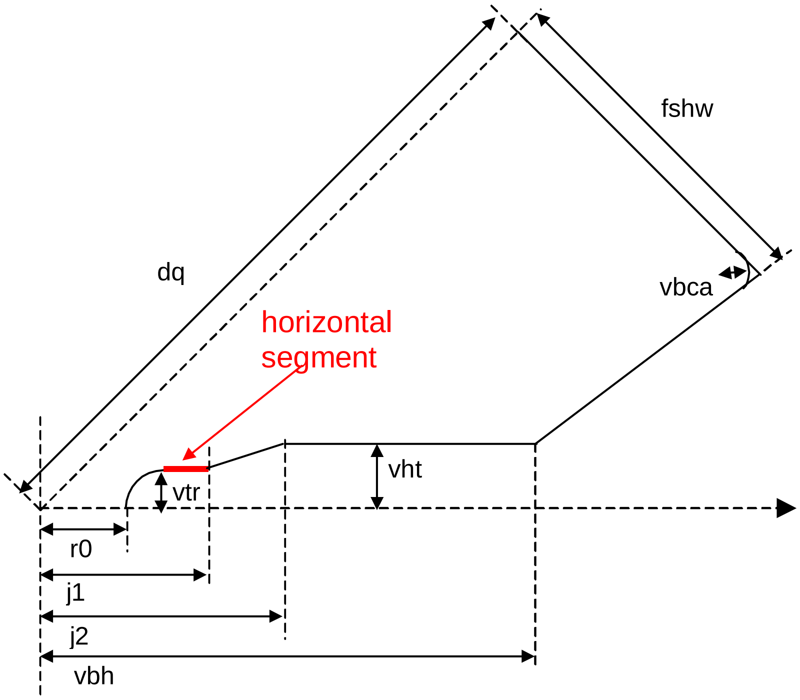


figure 3 : « conventional » transverse section

The transverse section that we describe as « conventional », presents the following geometrical parameters (figure 3) :

- r_0 = mean aperture, set by the beam dynamics.
- *vtr* = vane tip radius.
- *j1* = extremity of the horizontal segment.
- *j2* = extremity of the sloping segment.
- *vht* = electrode half thickness.
- *vbh* = electrode basis half height.
- *fshw* = flat side half width.
- *dq* = distance between the longitudinal axis and the outer quadrant.

Some comments can be added :

1. The mean-aperture r_0 and the vane-tip radius *vtr* are set by the beam dynamics.
2. The *j1* parameter is set to a minimum value in prospect to machine the circular electrode tip with a specific milling-cutter ([2]). With the value used in this paper, the minimum length of the horizontal segment is 6 mm whatever is the electrode tip modulation.
3. For all the dissipated powers computed in this study, the inter-vane voltage V is set to 100 kV.

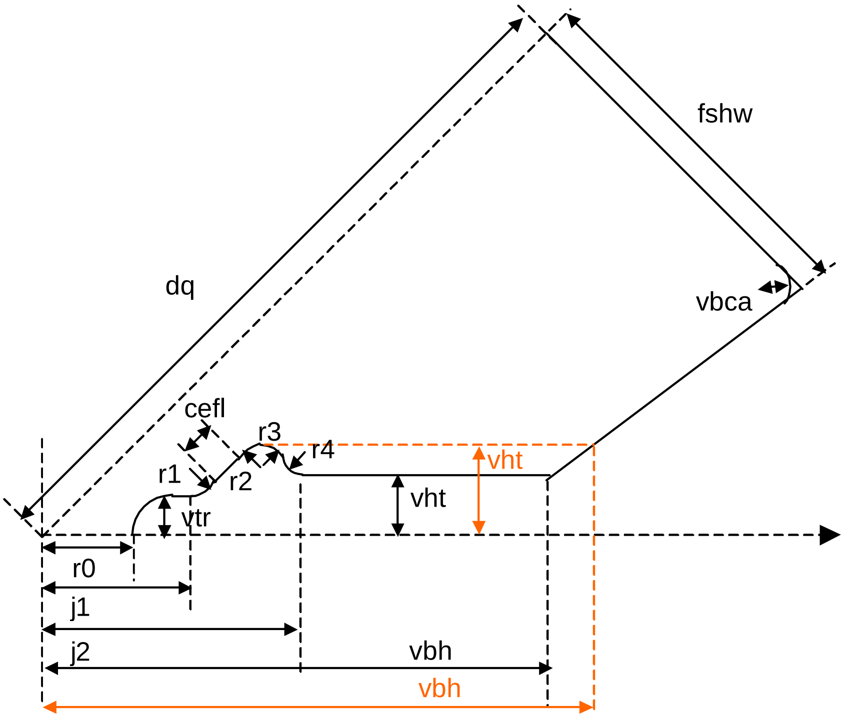


figure 4 : « crocodile » transverse section parameters

In the « crocodile » profile transverse section, the following geometrical parameters have been added (figure 4) :

- *r1* = radius of the circular segment connecting the horizontal segment and the 45° sloped segment.
- *cefl* = crocodile eyeball 45° sloped segment length.
- *r3, r4 & r5* = radii of the circular "eyeball".

3 Size reduction test at 176,1 MHz RFQ

3.1 Reference “conventional” 176 MHz RFQ transverse section

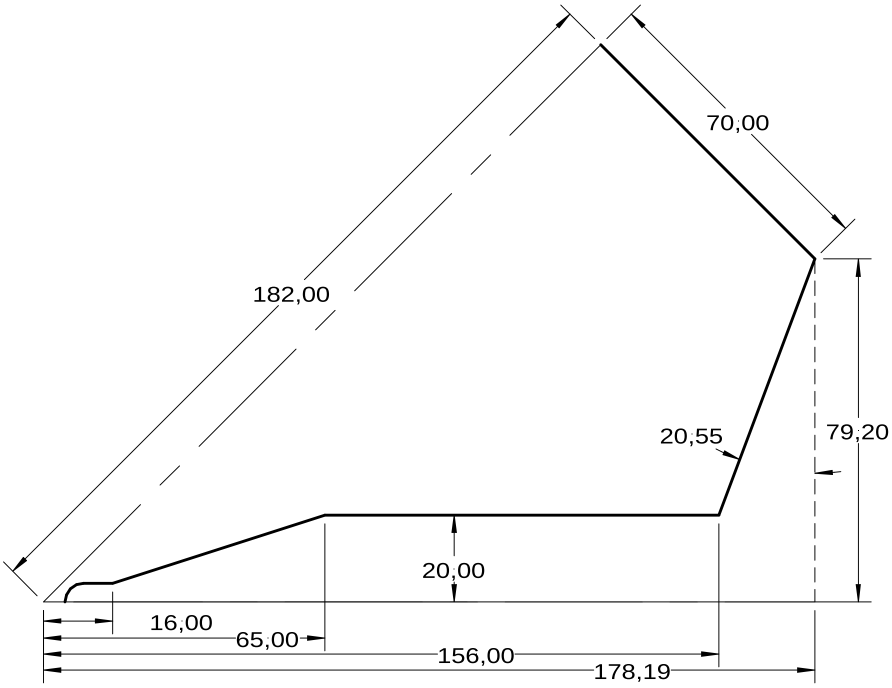


figure 5 : RFQ transverse section (176,1 MHz, v3)

In reference to the beam dynamics, the mean-aperture r_0 is set to 5 mm, and the vane-tip radius vtr=4,3 mm. The transverse section has been designed such a way that the quadrupole mode frequency is close to 176,1 MHz. The electrode half-width has been set constant and equal to 20 mm.

The first order dipole mode characteristics have been computed (see the following table).

	Frequency	Stored energy
Quadrupole mode	176,061 MHz	4 x 0,00167 J/cm
Dipole mode	171,105 MHz	4 x 0,00044 J/cm

From the resonance frequencies and the stored energies of the quadrupole and dipole modes, the equivalent circuit of the transverse section ([3]) has been computed :

L	C	Ca
24,42 nH.m	33,47 pF/m	2,2 pF/m

3.2 Size reduction test result

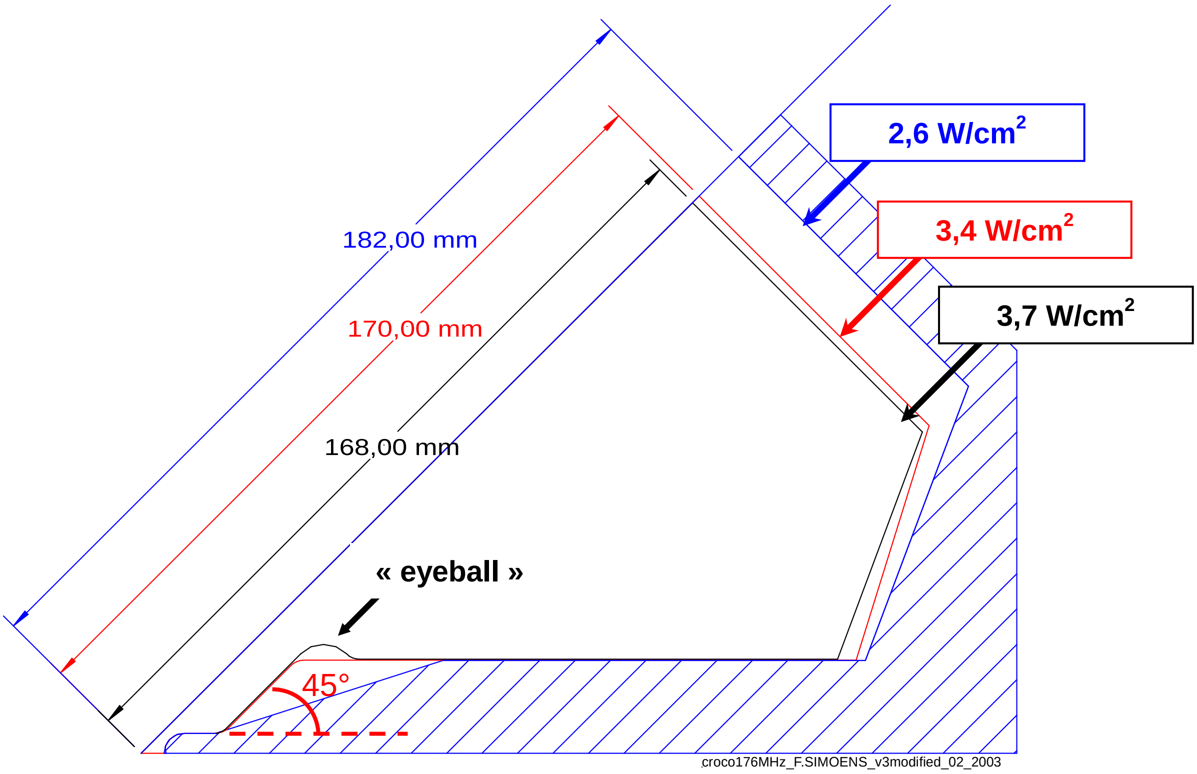


figure 6 : size reduction test of the 176MHz transverse section

First, the only modification has consisted in setting the slope of the electrode tip to 45° (see figure 6). That way, the capacitance has been increased by 15,6% (Table 1), and this variation has made possible a reduction of the distance between the longitudinal axis and the outer quadrant, dq, of 24 mm.

In a second step, a mechanical bump has been added (equivalent of the "crocodile eyeball", figure 6). This addition of matter allowed for the cavity size to be reduced a little further.

Table 1 : Equivalent circuit parameters of the transverse sections

	L [nH.m]	C [pF/m]	Ca [pF/m]
Reference v3 spiral2	24,42	33,47	2,2
Crocodile r1=r2=4, r3=r4=0, cefl=19, vht=20mm	21,09	38,71	2,49
Crocodile r1=3, r2=r3=7, r4=4, cefl=23, vht=20,27mm	20,29	40,20	2,50

Table 2 : Size and power dissipations variations

	dq [mm]	Dia [mm]		P 1quadrant [W/cm]	Ptotal [W/cm]		Pmax [W/cm²]	
Reference v3 spiral2	182	364		127,2	508,8		2,60	
Crocodile r1=r2=4, r3=r4=0, cefl=19, vht=20mm	170	-24	-6,6%	161,2	+26,7%		3,41	+31,2%
Crocodile r1=3, r2=r3=7, r4=4, cefl=23, vht=20,27mm	168	-28	-7,7%	171,3	+34,7%		3,68	+41,5%

Conclusion:

At that frequency, the dissipated power (Ptotal) and the maximum surface power density (Pmax) are inversely proportional to 5 times the reduction in cavity size (see Table 2). Since the levels of power dissipations observed in the "conventional design" of the order of 2,5 W/cm are already a matter of concern in terms of cooling, it is not advisable to increase them any more. The cavity size reduction achieved with the crocodile profile principle can be considered as overpriced.

4 Size reduction test at 88,05 MHz RFQ

4.1 Reference "conventional" 88 MHz RFQ transverse section

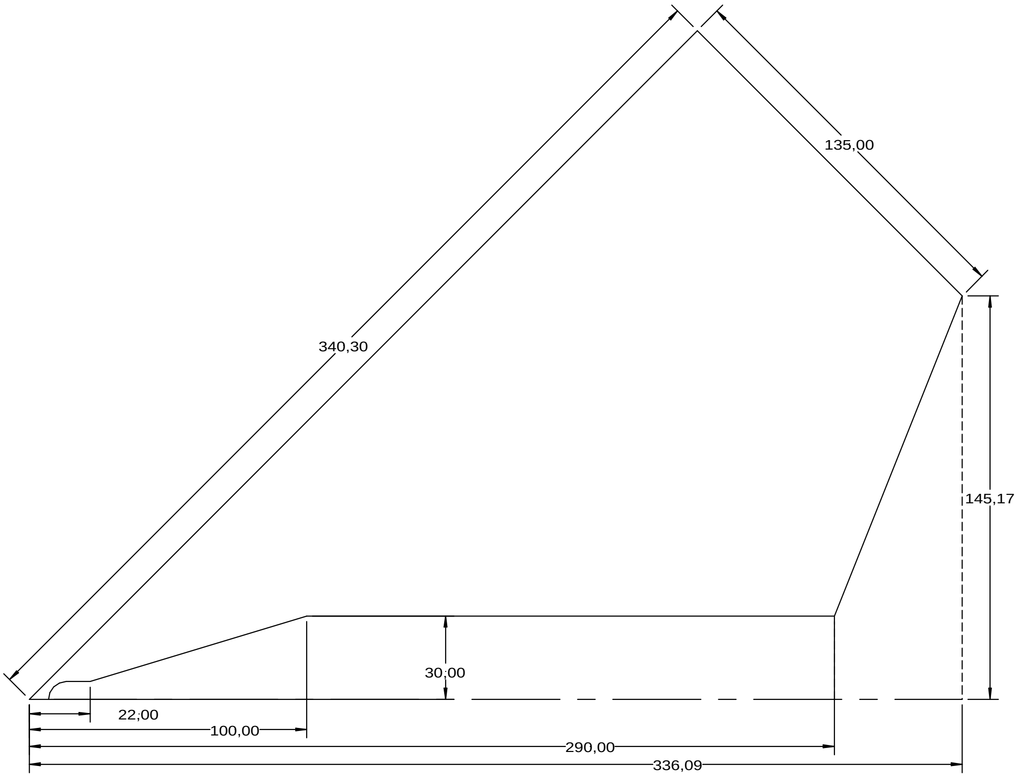


figure 7 : 88,05 MHz RFQ transverse section (Spiral2, v3)

At 88,05 MHz, the mean-aperture r_0 and the vane-tip radius *vtr* have been set respectively equal to 7 mm, and 6,375 mm.

The first order quadrupole and dipole mode characteristics have been computed :

	Frequency	Stored energy
Quadrupole mode	88,05 MHz	4 x 0,00183 J/cm
Dipole mode	85,77 MHz	4 x 0,00049 J/cm

With these values, the parameters of the equivalent circuit is :

L	C	Ca
89,28 nH.m	36,59 pF/m	2,6 pF/m

4.2 Size reduction test result

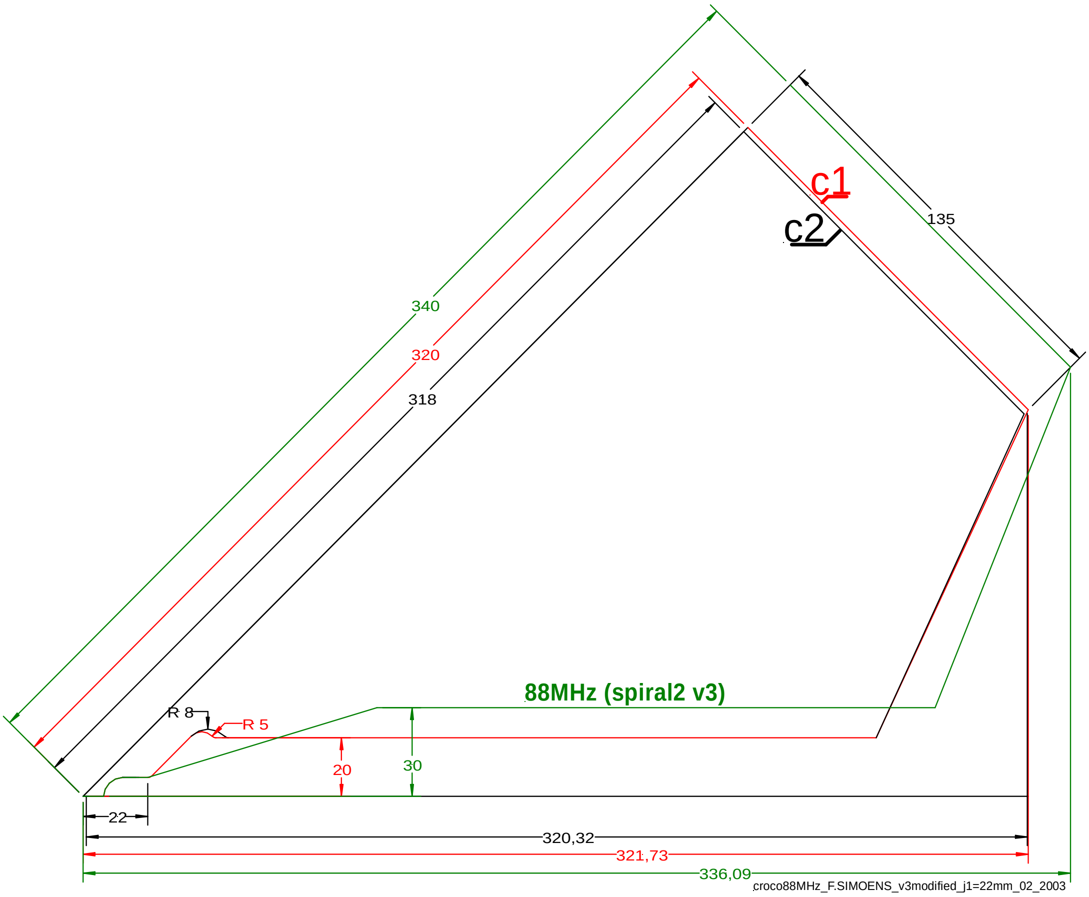


figure 8 : c1 and c2 « crocodile » profile tests at 88 MHz

According to mechanical experts, proper cooling imposes the minimum value of electrode half-width to be 20 mm. Two first designs c1 and c2 have been computed by setting vht=20 mm and by stating that the *j1* geometrical parameter is kept constant and equal to 22 mm (figure 8).

Table 3 : Equivalent circuit parameters of the transverse sections

	L [nH.m]	C [pF/m]	Ca [pF/m]
Reference v3 spiral2	89,28	36,59	2,6
Crocodile **„c1“** r1=r4=2, **r2=r3=5**, cefl=19, vht=19,81mm, vbh=270, fshw=135	83,03	39,47 (+7,9%)	3,15
Crocodile **„c2“** r1=r4=2, **r2=r3=8**, cefl=19, vht=19,81mm, vbh=270, fshw=135	82,20	39,74 (+8,6%)	3,18

Table 4 : Size and power dissipations variations

	dq [mm]	Dia [mm]		$P_{1quadrant}$ [W/cm]	Ptotal [W/cm]	Pmax [W/cm^2]	
Reference v3 spiral2	340,3	680		51,17	204,7	0,54	
Crocodile **„c1“**	320	-40	-5,9%	56,63	+10,7%	0,61	+12,9%
Crocodile **„c2“**	318	-44	-6,9%	57,44	+12,24%	0,63	+16,7%

Discussion: At that frequency, the maximum surface power density is inversely proportional to 2 times the reduction in cavity size. So in that situation, dissipation growth can be positively balanced by size reduction, and consequently a significant cost reduction may be expected.

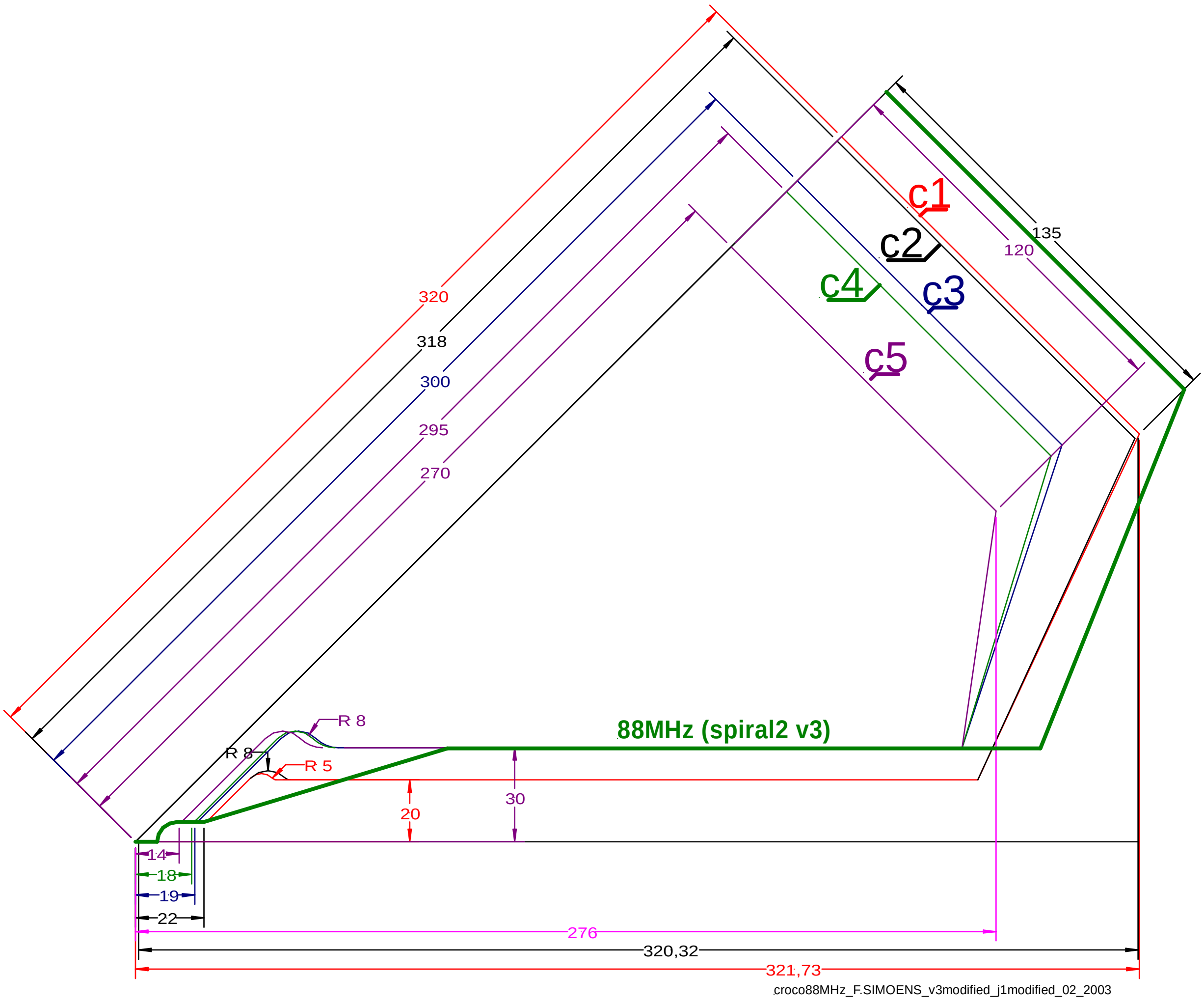


figure 9 : « crocodile » profile evolution while reducing j1 from 22 mm to 14 mm

Since the cavity diameter cannot be any more meaningfully reduced while keeping *j1*=22 mm, the *j1* parameter has been reduced step by step. In a first approach, the electrode width has been simultaneously increased to 30 mm (i.e. equal to the reference design value v3).

Table 5 : Equivalent circuit parameters of the transverse sections

	L [nH.m]	C [pF/m]	Ca [pF/m]
Reference v3 Spiral2	89,28	36,59	2,6
Crocodile **„c3“ j1=19 mm**, r1=2, r2=r3=8, r4=10, cefl=37, vht=30,2mm, vbh=265, fshw=120	66,49	48,80 (+33,4%)	3,39
Crocodile **„c4“** : **j1=18mm**, r1=2, r2=r3=8, r4=10, cefl=37, vht=30,2mm, vbh=265, fshw=120	64,68	50,22 (+37,3%)	3,43
Crocodile **„c5“ : j1=14mm**, r1=2, r2=r3=8, r4=10, cefl=37, vht=30,2mm, vbh=265, fshw=120	54,79	59,33 (+62,2%)	3,69

In the « j1=14 mm » case, the equivalent capacitance has been almost doubled in comparison with the reference v3 Spiral2 transverse section.

Table 6 : size and power dissipations variations (j1 modified)

	dq [mm]	Dia [mm]		P 1quadrant [W/cm]	Ptotal [W/cm]	Pmax [W/cm^2]	
Reference v3 spiral2	340,3	680		51,17	204,7	0,54	
Crocodile **j1=19 mm**, r1=2, r2=r3=8, r4 x 5 fl=37, vht=30,2mm, vbh=265, fshw=120	300	-80	-11,7 %	80,17	+56,7 %	0,94	+74,1 %
Crocodile **j1=18mm**, r1=2, r2=r3=8, r4 x 5 l=37, vht=30,2mm, vbh=265, fshw=120	295	-90	-13,2 %	83,99	+64,14 %	0,99	+83,3 %
Crocodile **j1=14mm**, r1=2, r2=r3=8, r4 x 4 =37, vht=30,2mm, vbh=265, fshw=120	270	-140	-20,6 %	109,94	+83,68 %	1,37	+153,7 %

Conclusion:
As long as j1 was kept great enough (cases c1 and c2), we have observed that the capacitance increase was leading to a reasonable increase of the dissipated powers. In the c3 to c5 cases, the capacitance increase is such that the power dissipations and the maximum power deposits are greatly increased, being inversely proportional to about 4 to 5 times the size reduction. But the total linear power dissipation is still smaller than the one found in the 176 MHz reference transverse section, 440 W/cm (c5) compared to 508 W/cm (v3 reference design). So depending on the material and on the mechanical design of the RFQ, the principle of the "crocodile profile section" can be applied to the size reduction of the cavity in spite of the consequent increase in power consumption. The most concerning aspect is surely the maximum local power deposit that becomes very important, and that can imply localized high power dissipations in the 3d end regions of the cavity.

4.3 Extreme size reduction pursuit

As a stubborn "crocodile Dundee" would do, the increase of the capacitance has been pursued till the "crocodile profile" 88 MHz cavity size is close to the 176 MHz reference transverse section. A big outgrowth has been added on the crocodile forehead, and as a consequence, a geometry has been found resonating at 88 MHz (figure 10).

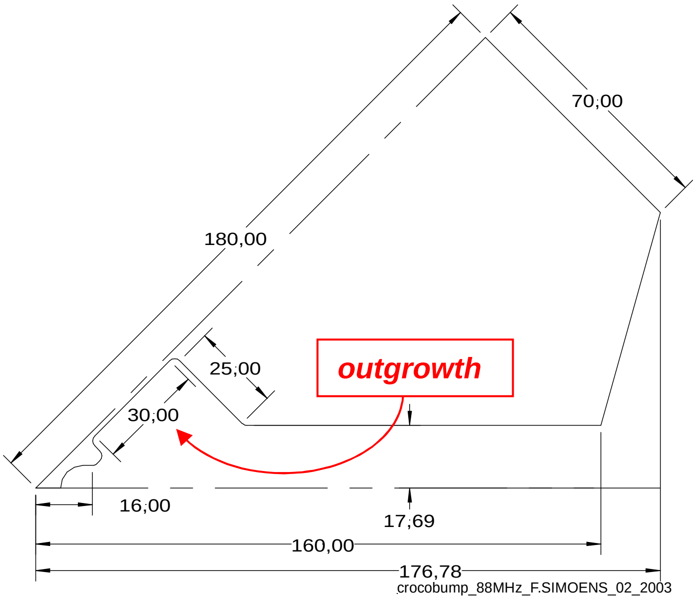


figure 10 : modified « crocodile » profile resonating at 88 MHz

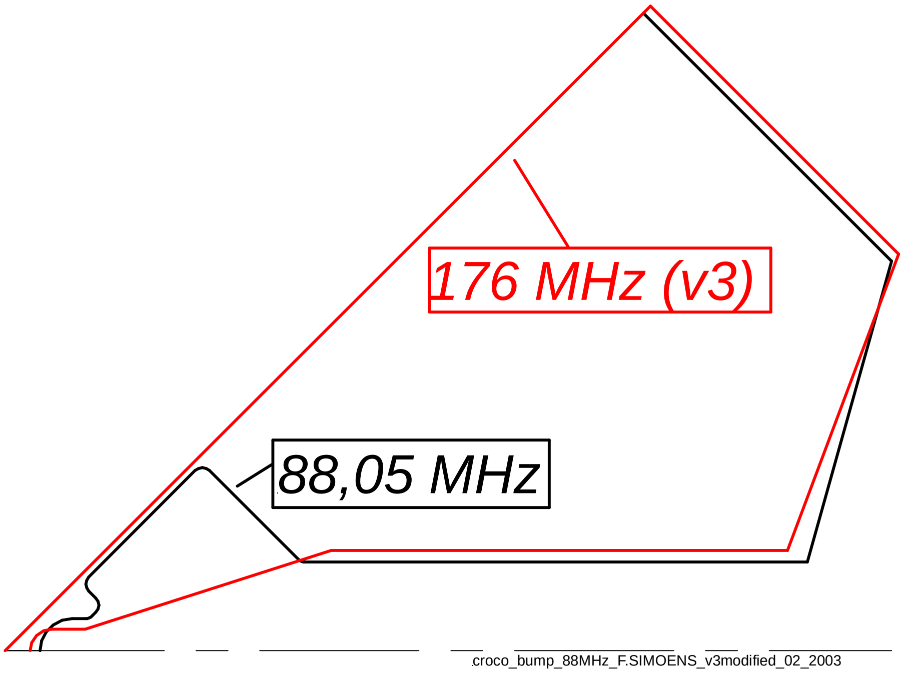


figure 11 : comparison of the reference 176 MHz section with a 88 MHz crocodile profile

Table 7 : Equivalent circuit parameters of the transverse sections

	L [nH.m]	C [pF/m]	Ca [pF/m]
Reference 88 MHz v3 spiral2	89,28	36,59	2,6
Extreme 88MHz „crocodile“ profile	23,27	138,26 (+278%)	3,55

Table 8 : Size and power dissipations variations

	dq [mm]	Dia [mm]		P 1quadrant [W/cm]	Ptotal [W/cm]	Pmax [W/cm^2]	
Reference 88 MHz v3 spiral2	340,3	680		51,17	204,7	0,54	
Extreme 88 MHz „crocodile“ profile	180	-320	-47%	395	***x 7,7***	7,4	***x 13,7***

The cavity size reduction (figure 11) implies an unacceptable increase (Table 8) of the total dissipated power (x 7,7) and of the highest power deposit point (x 13,7). These values are higher than the ones found in the 176 MHz design (510 W/cm & 2,6W/cm^2).

Conclusion :
Unless mechanical criteria show an essential interest in this size gain, this solution cannot be accepted.

4.4 Simple model explaining the observed tendency

In the central region, the quadrupole mode is characterized by a potential difference *V* between each pair of 2 conducting neighbouring vane-tips. This region where the electrical field dominates is represented as a lumped capacitance C par unit length, expressed in [F/m]. The longitudinal magnetic field flowing through the outer quadrant acts as a current load for each pair of adjacent conductors. This load is represented as a parallel "inverse" inductance per unit length L in [H.m]. For an $e^{j\omega t}$ time dependence of the fields, the current circulating on the outer wall is given by $I = j\omega CV$ [A/m].

The power loss can be computed as $P = 1/2\,RsI^2$ [W/m] where $Rs = \sqrt{\omega\mu_0/2\sigma}$ is the surface resistance of the cavity wall (in [ohm]). So $P \propto \omega^{5/2}(CV)^2$.

In the case of the extreme size reduction test, the path of the current is almost identical between the 'v3' 176 MHz profile and the 'rhino' 88 MHz. Consequently the equivalent inverse inductance is fairly the same (24,41 nH.m for v3 to compare to 23,27 nH.m for the rhino).

Since the capacitance is linked to the quadrupole frequency *f* and *L* by $f = 1\big/ 2\pi\sqrt{LC}$, the **capacitance** evolves between these 2 designs as : $\dfrac{f_{v3}}{f_{rhino}} = \dfrac{176}{88} = 2 = \sqrt{\dfrac{C_{88MHz}}{C_{176MHz}}}$.

The 'rhino' profile (88MHz) presents an equivalent capacitance 4 times greater than the 'v3' profile (176MHz). Indeed the computed values show a ratio $\dfrac{C_{rhino}}{C_{v3}} = \dfrac{138.26}{33.47} = 4.1$, that is a value close to 4.

Applying the simplified model, for a given voltage V, the **current ratio** must be :

$$\frac{I_{rhino}}{I_{v3}} = \frac{\omega_{rhino}C_{rhino}}{\omega_{v3}C_{v3}} = \frac{88}{176}4 = 2$$

Indeed we find a ratio equal to 2 between the average H field in the rhino profile (7772,49 A/m) and the one in the v3 section (3876,3 A/m).

So the 'modelled' power loss ratio is $\dfrac{P_{rhino}}{P_{v3}} = \left(\dfrac{\omega_{rhino}}{\omega_{v3}}\right)^{5/2}\left(\dfrac{C_{rhino}}{C_{v3}}\right)^2 = 2\sqrt{2} \approx 2{,}8$.

The Superfish power losses show a ratio $\dfrac{P_{rhino}}{P_{v3}} = \dfrac{1580}{509} = 3{,}1$ that is of the order of 2,8. The difference comes from the fact that the optimized profiles are such that :

1. 1- $\dfrac{f_{rhino}}{f_{v3}} = \left(\dfrac{88{,}73}{176{,}061}\right) = \dfrac{1}{1{,}98} > 0{,}5$
2. 2- $\dfrac{C_{rhino}}{C_{v3}} = 4.1 > 4$

This model shows that when the outer quadrant is kept almost unchanged, the frequency lowering goes with a power loss increase such that $\dfrac{P_2}{P_1} = \left(\dfrac{\omega_1}{\omega_2}\right)^{3/2}$

5 Mean aperture variation compensation test

In RFQs where the mean aperture r0 varies longitudinally, this equivalent capacitance modulation is usually compensated by the outer quadrant geometry alteration, and consequently the inductive component changes. That way the resonance frequency can be kept constant from cell to cell and the RFQ is a homogeneous transmission line in terms of transverse cut-off.

One interest of the ‘crocodile profile’ principle would be to achieve the r0 compensation by modifying the electrode tip itself since the r0 variation modifies only the extreme end of the electrode. This capacitance compensation could be realized by altering the ‘crocodile eyeball’ volume as the figure 12 shows.

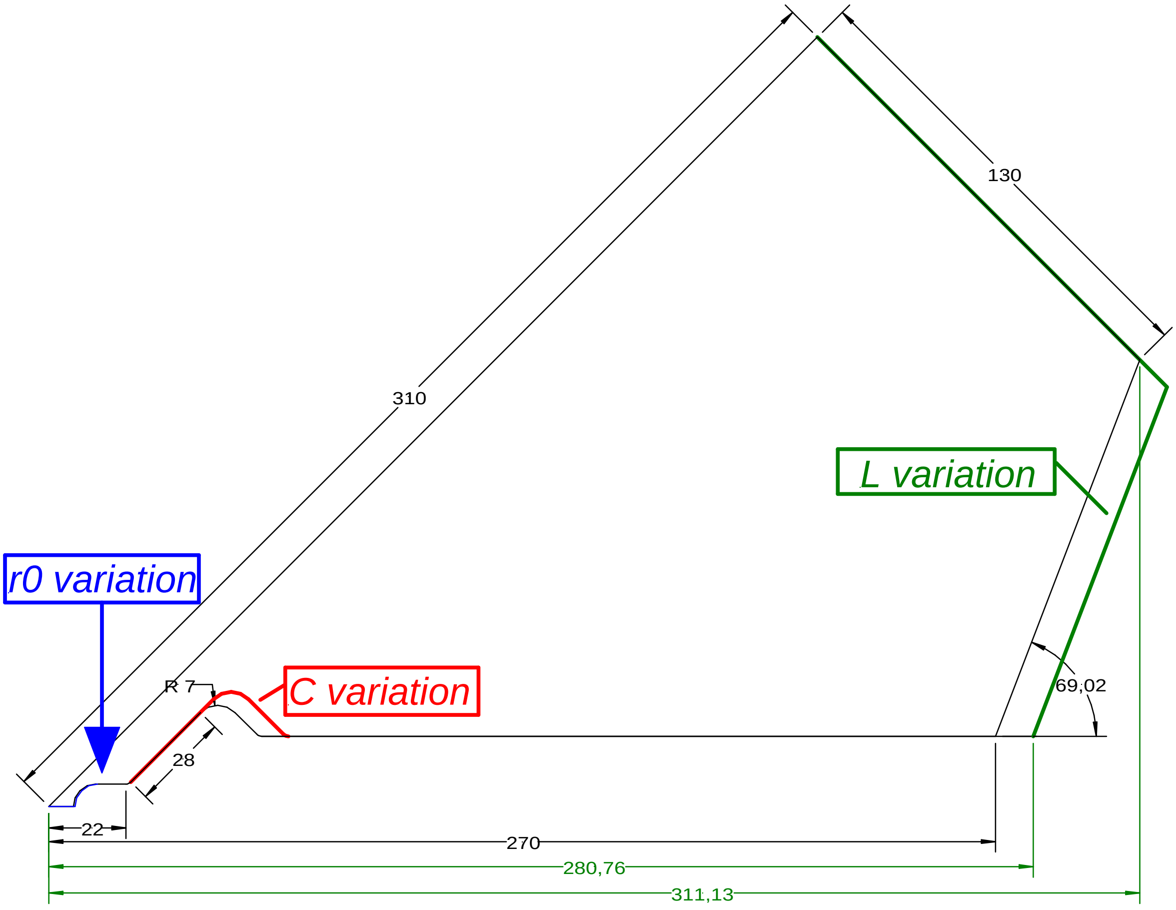


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figure 12 : r0 variation compensation test

5.1 Comparison of the capacitive and inductive compensations

The ‘crocodile profile’ section has been computed for a 7 mm mean aperture and an electrode half-width vht=20 mm (black profile of figure 12). In the reference 88,05 MHz beam dynamic design (APS Spiral2), r0 evolves longitudinally up to 7,5 mm. So, all other geometrical parameters being equal, r0 has been set to this 7,5 mm maximum value. This change has brought the quadrupole frequency up to 89,63 MHz and has gone with a –3% decrease of the equivalent capacitance (see the following tables).

Two compensations have been tested :

1- A **capacitive compensation**, that has lead to a higher bump of the electrode tip (“C variation” of the figure 12).
2- An **inductive compensation**, achieved by translating the vane basis while keeping a constant angle of 69° (“L variation of figure 12). That way, the transverse section surface has been stretched out.

Table 9 : Equivalent circuit parameters of the transverse sections

	f_O [MHz]	f_D [MHz]
Reference v3 spiral2	88,05	88,05
r0=7 mm Crocodile r1=r4=2, r2=r3=7, cefl=19, vht=20, vbh=270, fshw=130, dq=310	88,03	86,00
r0=7,5 mm Crocodile „“ r1=r4=2, r2=r3=7, cefl=19, vht=20, vbh=270, fshw=130, dq=310	89,63	87,49
r0=7,5 mm ⇒ Capacitive compensation Crocodile r1=r4=2, r2=r3=7, **cefl=33,5**, vht=20, vbh=270, fshw=130, dq=310	88,05	87,49
r0=7,5 mm ⇒ Inductive compensation Crocodile r1=r4=2, r2=r3=7, cefl=19, vht=20, **vbh=281, fshw=141**, dq=310	87,98	85,89

Table 10 : Equivalent circuit parameters of the transverse sections

	L [nH.m]	C [pF/m]	Ca [pF/m]
Reference v3 spiral2	89,28	36,59	2,6
Crocodile **r0=7 mm**	78,46	41,67	2,91
Crocodile **r0=7,5 mm**	78,27 (-0,2% / 78,46)	40,28 (-3% / 41,67)	2,73
r0=7,5 mm ⇒ Capacitive compensation	78,01 (-0,3% / 78,27)	41;89 (+4% / 40,28)	2,75
r0=7,5 mm ⇒ Inductive compensation	81,4 (+4% / 78,27)	40,20 (-0,2% / 40,28)	2,51

Table 11 : Power dissipations variations

	$P_{1quadrant}$ [W/cm]	Ptotal [W/cm]	Pmax [W/cm^2]	
Reference v3 spiral2	51,17	204,7	0,54	
Crocodile **r0=7 mm**	62,26	+21,7% / 204,7	0,69	+27,8% / 0,54
Crocodile **r0=7,5 mm**	69,63		0,77	
r0=7,5 mm ⇒ Capacitive compensation	72,13	+15,8% / 7mm	0,79	+14,5% / 0,69
r0=7,5 mm ⇒ Inductive compensation	68,38	+9,8% / 7mm	0,74	+7,3% / 0,69

Conclusion

As the previous table shows, the capacitive compensation entails slightly greater increases of the power consumption and of the local maximum power deposit than the inductive compensation. This tendency can be accepted, since on the other hand, the ‘crocodile profile’ offers the following advantages :

- It implies mechanical changes strictly localized in the central region. The geometry of the outer quadrants is kept constant along the structure, making possible the choice of low cost mechanical designs for the main cavity body.
- The crocodile profile adds machining complexity to a region that is already subjected to severe mechanical tolerances. Since specific milling tools are needed to machine the electrode tips modulations, they could be made compatible with the ‘crocodile profile’ evolutions.

5.2 Test of the effect of the r0 variation in a ‘conventional’ profile / in a ‘crocodile’ profile

Table 12 : Equivalent circuit parameters of the transverse sections

	f_Q [MHz]	f_D [MHz]
Reference v3 spiral2 **r0=7 mm**	88,05	88,05
Reference v3 spiral2 **r0=7,5 mm**	89,88	87,45

In the 88 MHz ‘conventional’ design, all other geometrical parameters being equal, r0 has been set to 7,5 mm. This change has gone with a quadrupole frequency increase up to 89,88 MHz (Table 12) and a -3,77% decrease of the equivalent capacitance (Table 13).

So the r0 change leads to a smaller capacitance variation in the ‘crocodile profile’ case than in the ‘conventional’ transverse section. In some ways, the crocodile profile brings a relative immunity to the electrode tip geometrical change. This benefit is not negligible since, in that region, the field error sensitivity is very high owing to high field gradients and, moreover, cooling is difficult because of the small electrode extremity width.

Table 13 : Equivalent circuit parameters of the transverse sections

	L [nH.m]	C [pF/m]	Ca [pF/m]
Reference v3 spiral2 **r0=7 mm**	89,28	36,59	2,60
Reference v3 spiral2 **r0=7,5 mm**	89,04	35,22 (-3,77%)	2,46

6 Conclusion

For small frequencies (typically 90 MHz) the principle of the "crocodile profile section" can be applied to the size reduction of the cavity in spite of the consequent increase in power dissipation. The relevance of its application mainly depends on the material and on the mechanical design of the RFQ. A special care must be paid to the maximum local power deposit that can imply localized worrying high power dissipations in the 3d end regions of the cavity.
This study has shown that at frequency around 170 MHz, the size reduction is overpriced in terms of power consumption.

The application of the "crocodile" profile principle to RFQ transverse section can be relevant to compensate the mean aperture variation. This capacitive compensation implies slightly greater increases of the power consumption and of the local maximum power deposit than the inductive compensation. But this evolution can be easily accepted, since on the other hand, the 'crocodile profile' offers the following advantages :

- It implies mechanical changes strictly localized in the central region. The geometry of the outer quadrants is kept constant along the structure, making possible the choice of low cost mechanical designs for the main cavity body.
- The crocodile profile adds machining complexity to a region that is already subjected to severe mechanical tolerances. Since specific milling tools are needed to machine the electrode tips modulations, they could be made compatible with the 'crocodile profile' evolutions.

Another advantage of the crocodile profile is that, in some ways, the crocodile profile brings a relative immunity to the electrode tip geometrical change. This benefit is not negligible since, in that region, the field error sensitivity is very high owing to high field gradients and, moreover, cooling is difficult because of the small electrode extremity width.

References

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