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Range of possible beam current in Linac4

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Abstract

Linac4 is a new accelerator under construction at CERN. It is designed to accelerate H- ions to 160MeV, for injection into the existing Proton Synchrotron Booster (PSB). It is also the front-end of the SPL Linac, a high energy proton driver that will reach the energy of 5GeV. The Linac baseline design has been done for a nominal beam peak current of 70mA but it will certainly have to deal with different currents. 132 out of 155 quadrupoles in the Linac are permanent magnets, this choice of using PMQ having fixed gradient, mainly in the DTL and in the CCDTL may then entail issues concerning the beam transverse matching and quality from current different from the nominal one. In this paper, we present the beam dynamics performances in Linac4 obtained for different currents.

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Introduction

The low energy section of Linac4 comprises a 45 keV H- ion source, a LEBT (Low Energy Beam Transport), a 352.2 MHz Radio Frequency Quadrupole and a 3 MeV Chopper-Line. The beam is further accelerated through a Drift Tube Linac to 50MeV, a Cell-Coupled Drift Tube Linac to 100 MeV and a PI Mode Structure up to the final energy of 160MeV. All these structures were matched for a 70 mA nominal peak current but should be able to keep the same beam quality performances for all the currents from 20 to 100mA. In order to demonstrate that the present design of Linac4 is capable to accept such a large current range, end-to-end simulations were performed with TraceWin and Parmteqm codes from the RFQ to the PIMS.

I Radio Frequency Quadrupole

The Linac4 RFQ accelerates the H- ions coming from the LEBT from 45keV to 3MeV. Transverse focusing and longitudinal acceleration are given by the modulation of the electrodes and their alternating polarity. It has been optimized for 70mA, but, by changing the input beam parameters, it can accelerate all the beam peak current from 0mA to 70mA and even more than 70mA considering that above this value, the transmission decreases almost as fast as the current increases. In the Table1 are listed the matched Twiss parameters at the RFQ input for the currents from 0 to 100mA. Figure1 shows the RFQ transmission, the Figure2 the evolution of Twiss parameters and the Figure3 the input beam profiles for 0 and 100mA. These simulations were done with Parmteqm [1] and Toutatis [2] codes.

Current (mA)	Alpha	Beta (mm/mrad)	Transmission (%)
0	0.805	0.0226	99.9
10	0.857	0.0237	99.2
20	0.91	0.0249	98.7
30	0.966	0.0261	98.1
40	1.022	0.0273	97.7
50	1.082	0.0286	96.8
60	1.142	0.0300	95.4
70	1.203	0.0313	93.4
80	1.267	0.0327	89.9
90	1.331	0.0342	84.8
100	1.396	0.0357	78.8

Table1: RFQ input Twiss Parameters and transmission from 0 to 100mA.

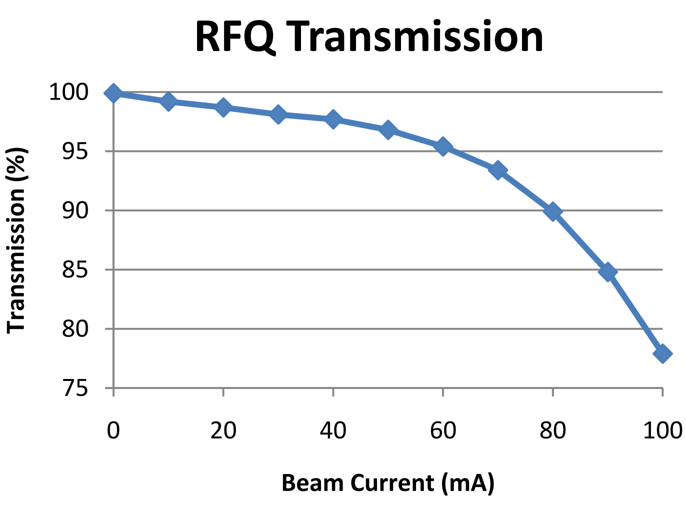

Figure1: RFQ transmission vs input beam current.

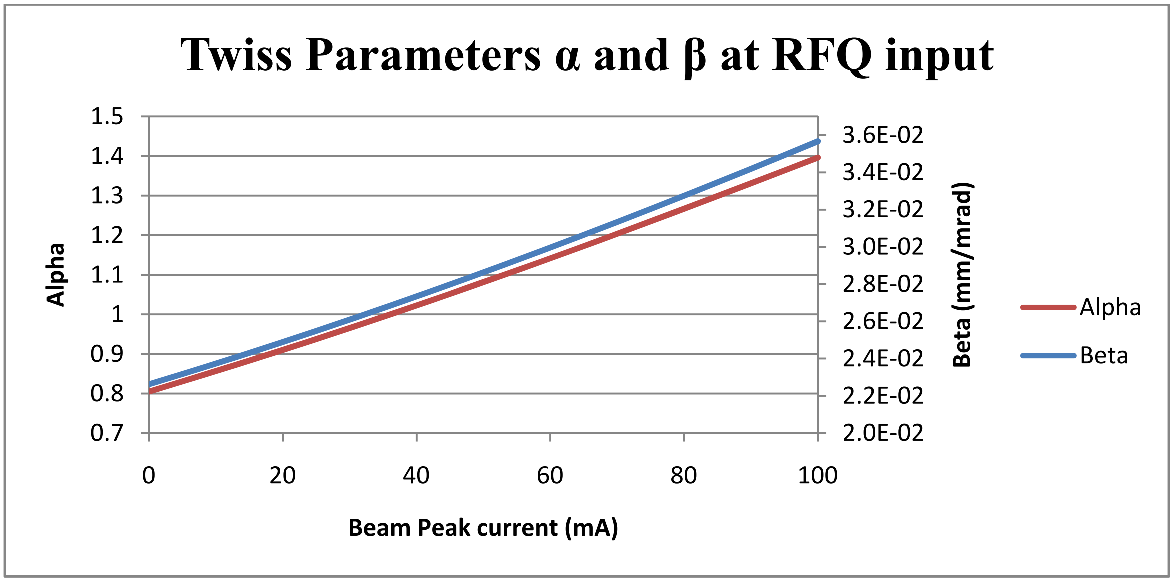

Figure2: Evolution of input Twiss parameters

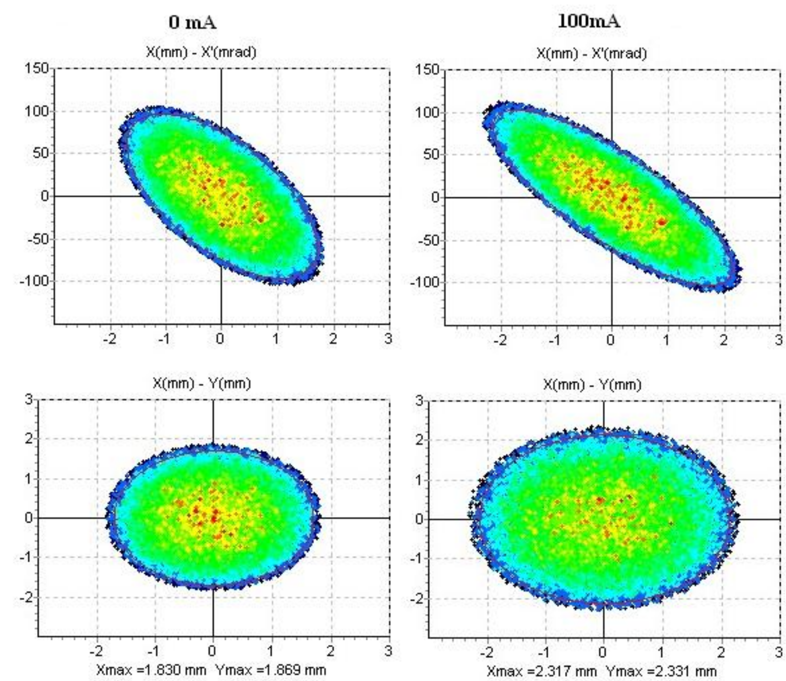

Figure3: RFQ input beam profile for 0 and 100mA

From all these data, we can conclude that the transmission on the RFQ is really degraded (less than 90% with generated input beam) above 80mA. The evolution of the Twiss parameters is smooth and we can match the beam coming from the LEBT for all the current until 100mA. We see in Figure3 that the stronger are the space charge forces, the bigger should be the input beam size in real space.

The main beam parameters at the output of RFQ are summarized in the Table2.

	Transmission (%) - mA	X RMS Emittance (π.mm.mrad)	Y RMS Emittance (π.mm.mrad)	Z RMS Emittance (π.deg.MeV)
20mA	98.9% - 19.7mA	0.271	0.271	0.111
40mA	97.4% -39mA	0.249	0.254	0.109
60mA	95.3% - 57.2mA	0.241	0.242	0.126
70mA-Nominal	93.3% - 65.3mA	0.239	0.242	0.132
80mA	89.9% - 71.9mA	0.240	0.240	0.137
100mA	78.8% - 78.8mA	0.237	0.240	0.146

Table2: Output RFQ beam parameters for different input beam currents.

From these values we can highlight some phenomena that happen in the RFQ: The higher the space charge, the larger the beam size (as already seen in Figure3 for the input beams). It entails more losses in transverse planes and bigger emittance in the longitudinal one. The losses in transverse planes explain why the transverse emittance decreases with the current. Starting from the six different currents 20, 40, 60, 70, 80 and 100mA at the RFQ input, we now get from it six input beams for chopper line with 19.7, 39, 57.2, 65.3, 71.9 and 78.8mA. Note that we did not make the choice of increasing the vane voltage, but an increase of 10% could be possible and results into better transmission for all the currents and especially for the high current cases. It could improve the transmission from 89.9 to 94.5% for 80mA and from 78.8 to 89% for 100mA.

II Chopper-line

The Linac4 MEBT line aims to remove 133 over 352 micro-bunches coming from the RFQ in order to reduce the losses at the injection into the PSB. It has also to match the 3MeV beam to the regular focusing structure that is the DTL. The Layout of the chopper-line is presented in Figure4.

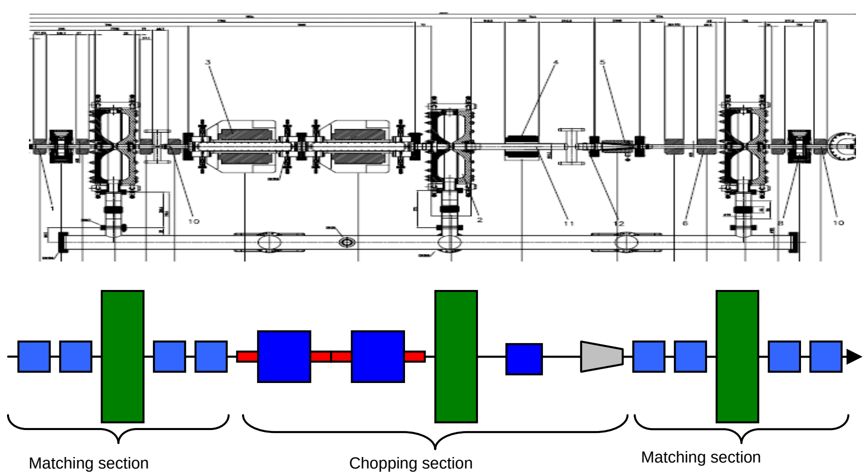

Figure4: Chopper-line layout.

Composed of two matching sections, the first one to match to beam from RFQ and the second one to the DTL, the middle part is called the "Chopping Section". In this part, a vertical electric field is generated by the chopper plates (in red in Figure4) in order to give a deflecting kick to the undesired bunches. This kick is then amplified by a defocusing quadrupole (in blue) and the beam is lost in the dump (in grey). As the eleven quadrupoles of the line are all electro-magnets, we are able to deal with different beam currents and to match to different Twiss parameters at the DTL input. All the simulations of MEBT, DTL, CCDTL and PIMS were done with TraceWin [3] code.

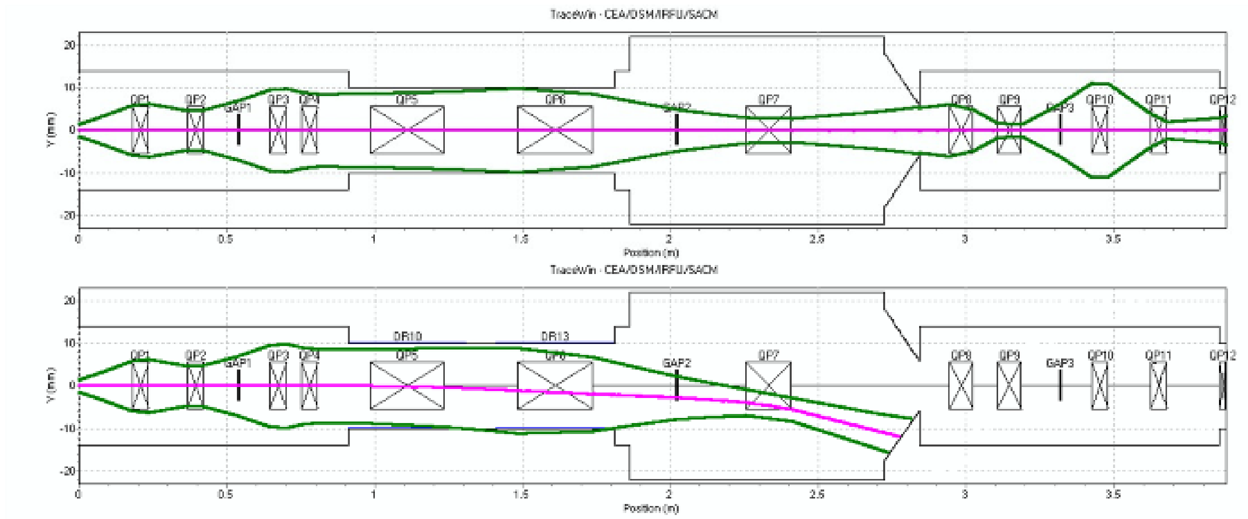

Figure5: Transmitted and chopped beam envelopes in MEBT

The figure above represents the vertical beam envelope in the chopper-line with and without voltage applied between chopping plates

1. Transmitted beam

The quadrupole settings of the chopper-line were arranged in order to insure a good chopping efficiency and a perfect matching to the DTL for the 6 different beams. The main beam parameters at the MEBT output are listed in the following table.

	Transmission (%) - mA	X RMS Emittance (π.mm.mrad)	Y RMS Emittance (π.mm.mrad)	Z RMS Emittance (π.deg.MeV)
20mA	99.1% - 19.5mA	0.282	0.283	0.116
40mA	98.7% - 38.5mA	0.275	0.275	0.120
60mA	95.6% - 54.7mA	0.270	0.286	0.140
70mA-Nominal	95.7% - 62.5mA	0.290	0.297	0.155
80mA	95.2% - 68.5mA	0.296	0.329	0.165
100mA	95.3% - 75.1mA	0.332	0.348	0.185

Table3: Chopper output beam parameters.

The transmission is better for the low current cases. Note that the difference of transmission between the 60 and 100mA cases are negligible (less than 1%) but not the emittance increases. If we refer to the Table2, transverse emittance increases in the MEBT are equal to 4.3%, 22% and 43% respectively for the 20, 70 and 100mA cases. For the longitudinal plane, the emittance behaves the same (4.3%, 17% and 27%).

2. Chopped beam

The eleven quadrupoles gradients have been changed to match the beam to the DTL and the chopping efficiency has been recovered for all the cases. In Table4, the remainder proportion of the beam are listed for 2 different voltages seen by the beam. It shows that for the 100mA cases, we would need more than 450V effective voltage between the chopper plates in order to completely chop the beam. In fact, the dump aperture is fixed but the beam size increases with the current. Higher is the current, higher should be the chopping voltage.

Remaining Beam	450V	400V
20mA	0%	0.14%
40mA	0%	0.25%
60mA	0%	0.32%
70mA-Nominal	0%	0.31%
80mA	0%	0.26%
100mA	0.2%	0.25%

Table4: Remaining beam after chopping.

III DTL, CCDTL and PIMS

We kept fix the focusing in the DTL and in the CCDTL considering that the focusing schemes are established by PMQs (Permanent Magnet Quadrupoles). We cannot, as we did in the chopper-line, adjust the line to current. We have to adjust the initial beam parameters to the line by using the 4 last quadrupoles of the MEBT. The regular focusing layout of the DTL can be adapted to many currents and emittances as far as we are able to adjust the beam parameters (Twiss parameters) at the input. The third buncher of the MEBT and its four last quads insure a proper matching to the regular DTL lattice. The transition CCDTL-PIMS needed some re-matching adjustments performed with the 4 first electromagnets of PIMS. The next figure shows the transverse envelope of the beam along DTL CCDT and PIMS for the different current cases, 20, 40, 60, 70, 80 and 100mA. For all these cases, the matching has been done to the same DTL-CCDTL channel thanks to the last part of the chopper-line. It means that only the 4 first quadrupole gradients of the PIMS were slightly adjusted. All the other parameters (quad gradients, gap phases and fields…) of the 65 meters line are the same for all the cases

We give in the following table the DTL input beam parameters for several currents.

Current (mA)	AlphaX	BetaX (mm/mrad)	AlphaY	BetaY (mm/mrad)	AlphaZ	BetaZ (mm/mrad)
0	0.901	0.112	-1.701	0.410	-0.0104	0.225
20	0.993	0.138	-1.952	0.475	-0.0122	0.299
40	1.082	0.158	-2.148	0.532	-0.0143	0.346
60	1.165	0.177	-2.309	0.577	-0.0161	0.378
80	1.192	0.181	-2.396	0.601	-0.0160	0.384

Table5: Matched DTL input Twiss Parameters from 0 to 80mA.

The values in Table5 bring us to the same conclusions than Table1 (RFQ case). The evolution of the input Twiss parameters is smooth, and we managed to reach them by using the matching section of the chopper-line.

The next figure shows the beam profiles at the DTL input for the 20 and 100mA cases. As expected, the beam size is bigger and the halo much more developed in the 100mA case.

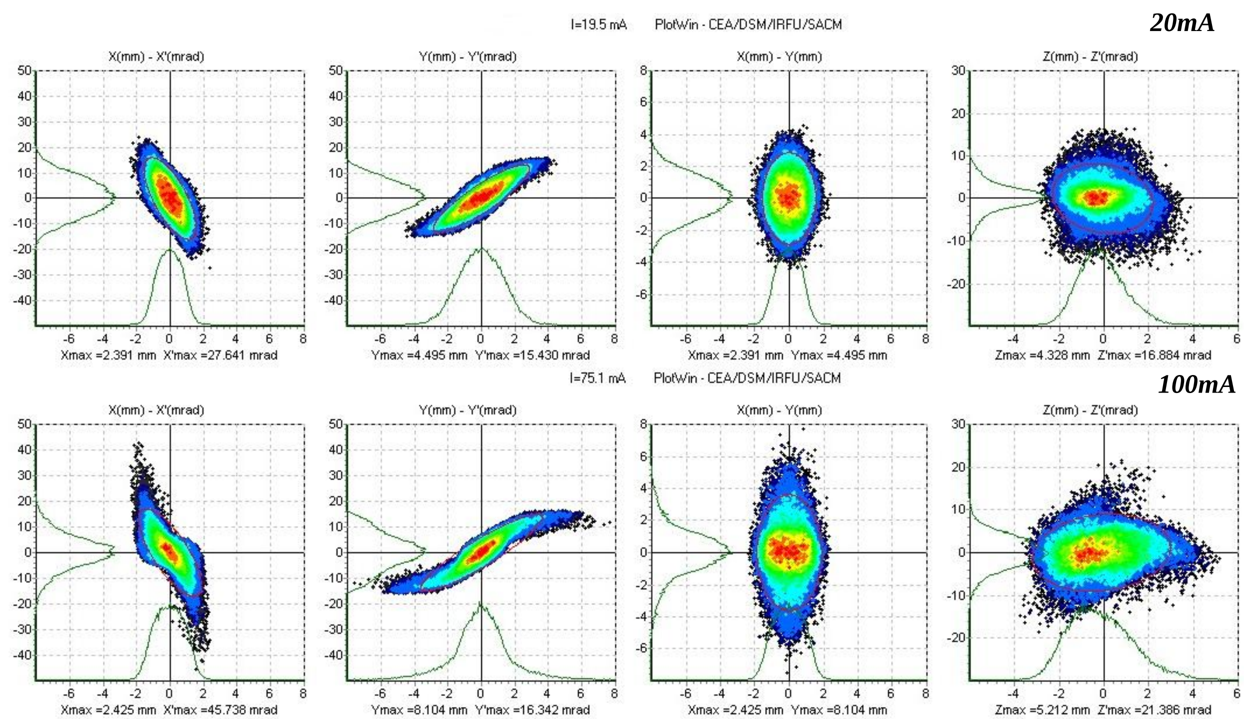

Figure6: DTL input beam profile for 20 and 100mA cases.

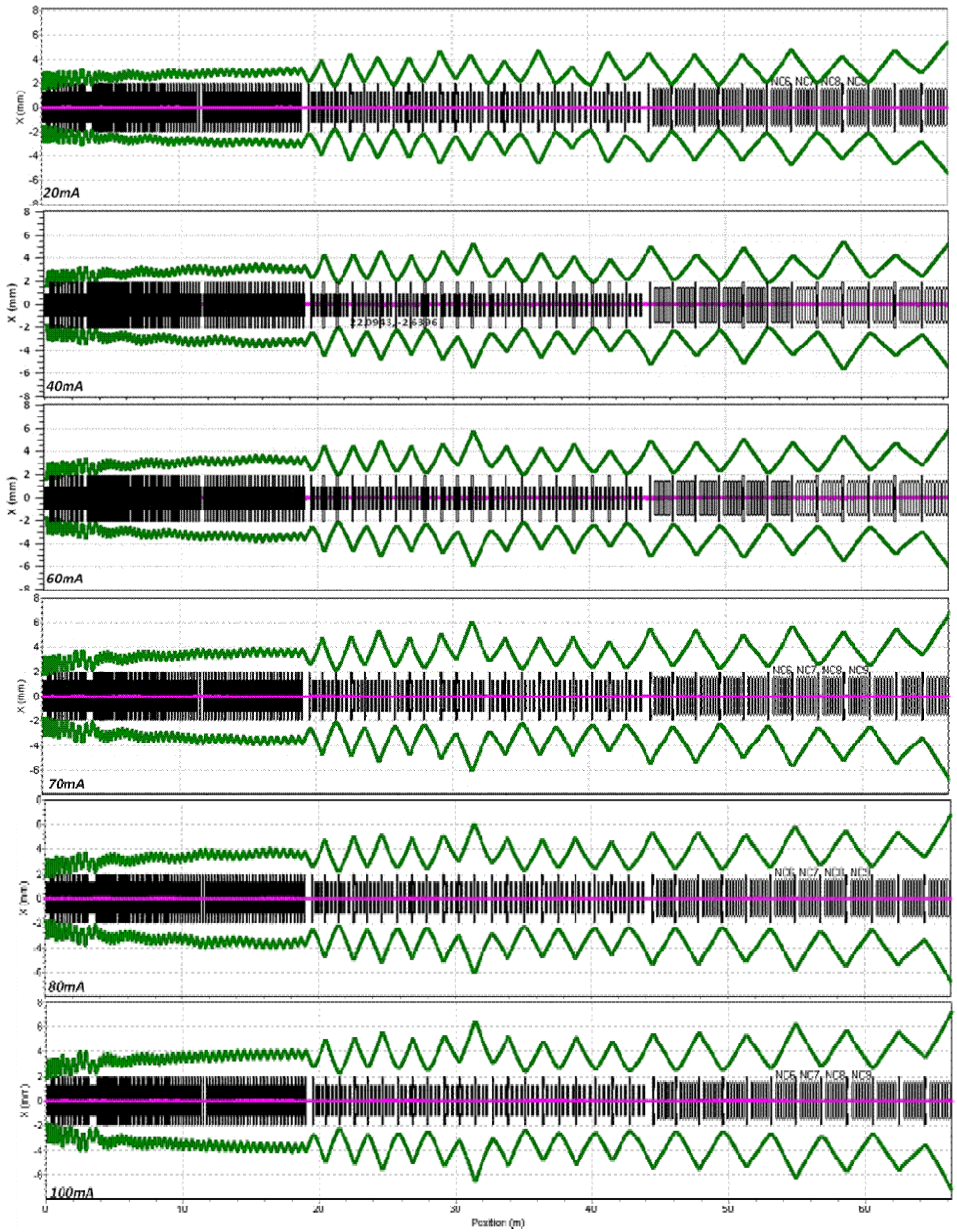

Figure7: Transverse beam envelope along DTL and CCDTL.

This figure shows that the beam is matched for all the 6 currents. Except for the 4 first quadrupoles of PIMS, all the settings are exactly the same, and, as done for the input beam. We can notice that the beam size is smaller at low currents. The main beam parameters at the outputs of the 3 structures are listed in the tables below.

	Transmission (%) - mA	X RMS Emittance (π.mm.mrad)	Y RMS Emittance (π.mm.mrad)	Z RMS Emittance (π.deg.MeV)
20mA	100% - 19.5mA	0.279	0.281	0.126
40mA	100% - 38.5mA	0.286	0.278	0.128
60mA	100% - 54.7mA	0.289	0.287	0.16
70mA-Nominal	100% - 62.5mA	0.31	0.309	0.186
80mA	100% - 68.5mA	0.335	0.334	0.202
100mA	99.97% - 75.1mA	0.372	0.360	0.222

Table6: DTL output beam parameters.

	Transmission (%) - mA	X RMS Emittance (π.mm.mrad)	Y RMS Emittance (π.mm.mrad)	Z RMS Emittance (π.deg.MeV)
20mA	100% - 19.5mA	0.287	0.283	0.129
40mA	100% - 38.5mA	0.289	0.288	0.136
60mA	100% - 54.7mA	0.299	0.299	0.167
70mA-Nominal	100% - 62.5mA	0.319	0.324	0.199
80mA	100% - 68.5mA	0.349	0.347	0.215
100mA	100% - 75.1mA	0.389	0.378	0.236

Table7: CCDTL output beam parameters.

	Transmission (%) - mA	X RMS Emittance (π.mm.mrad)	Y RMS Emittance (π.mm.mrad)	Z RMS Emittance (π.deg.MeV)
20mA	100% - 19.5mA	0.289	0.283	0.129
40mA	100% - 38.5mA	0.291	0.293	0.143
60mA	100% - 54.7mA	0.307	0.306	0.17
70mA-Nominal	100% - 62.5mA	0.337	0.327	0.199
80mA	100% - 68.5mA	0.363	0.352	0.212
100mA	100% - 75.1mA	0.416	0.382	0.232

Table8: PIMS output beam parameters.

Excepted few losses (< 0.5 ‰) in the DTL for the 100mA case, the transmission is 100% for all the cases in all the 3 accelerating parts. In the 3 structures, the conclusions on emittance increases are the same. The emittances increase more for the high current cases.

IV RFQ to PIMS Summary

The beam parameters evolutions are summarized in Table9 for the "RFQ to PIMS" simulations.

	Transmission (%) - mA	X RMS Emittance Increase	Y RMS Emittance Increase	Z RMS Emittance increase (from RFQ)
20mA	97.5% - 19.5mA	15.6%	13.2%	16.2%
40mA	96.2% - 38.5mA	16.4%	17.2%	31.2%
60mA	91.2% - 54.7mA	22.8%	22.4%	34.9%
70mA-Nominal	87.6% - 61.3mA	34.8%	30.8%	51.1%
80mA	85.6% - 68.5mA	45.2%	40.8%	54.6%
100mA	75.1% - 75.1mA	66.4%	52.8%	59.5%

Table9: Beam parameters evolution along Linac4.

Even if we noticed a bigger emittance increase in the RFQ for the low current case, the balance is reversed in chopper-line, DTL, CCDTL and PIMS. At the end of Linac4 we can conclude that transmission and emittance increases are correlated with the input beam current. Above 70mA input beam current, we can expect more than 10% of losses and emittance increases higher than 30% in transverse and 50% in longitudinal plane unless we increase the RFQ voltage.

The emittance evolutions from chopper-line to PIMS are represented in the following figures.

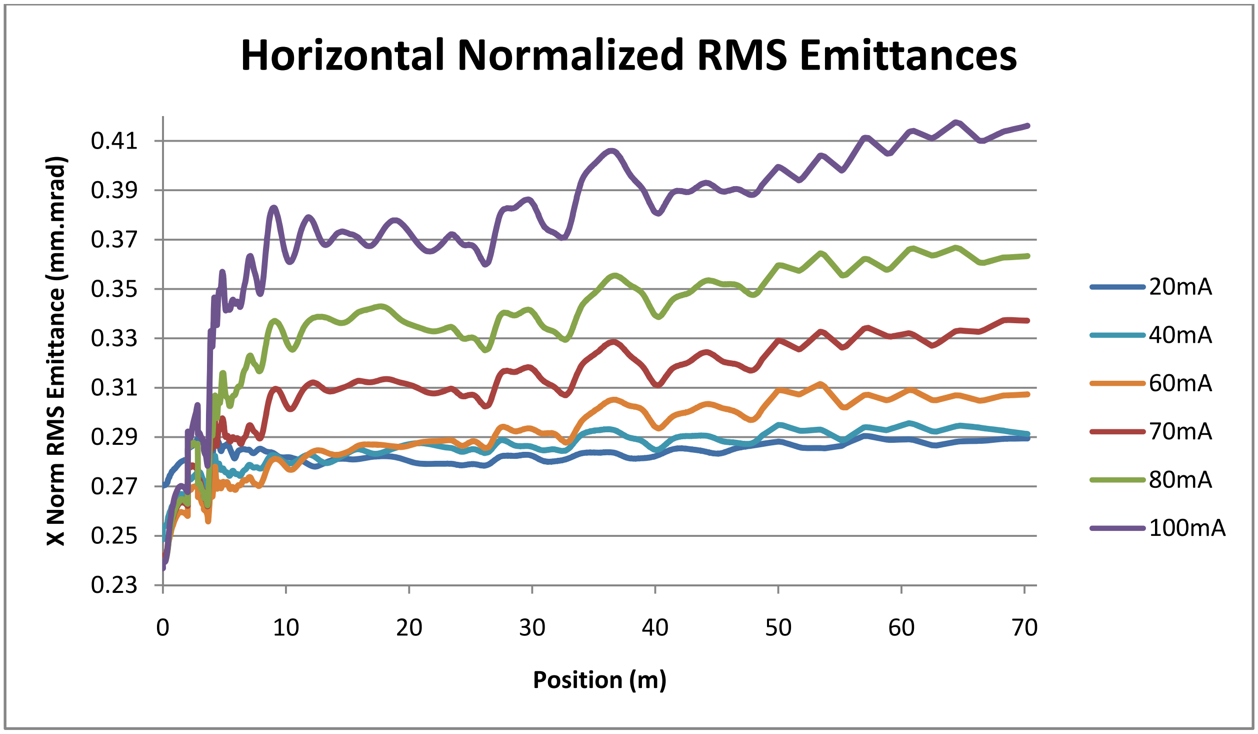

Figure8: Horizontal emittance evolution from MEBT to PIMS.

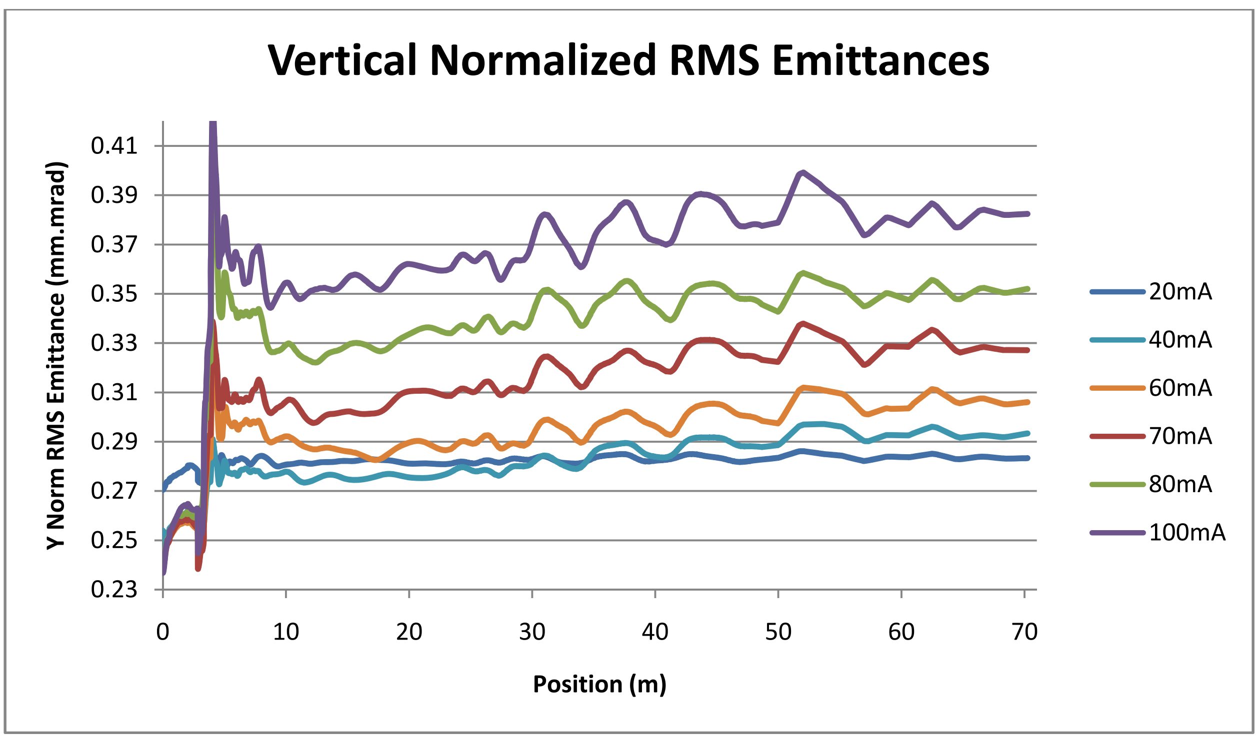

Figure9: Vertical emittance evolution from MEBT to PIMS.

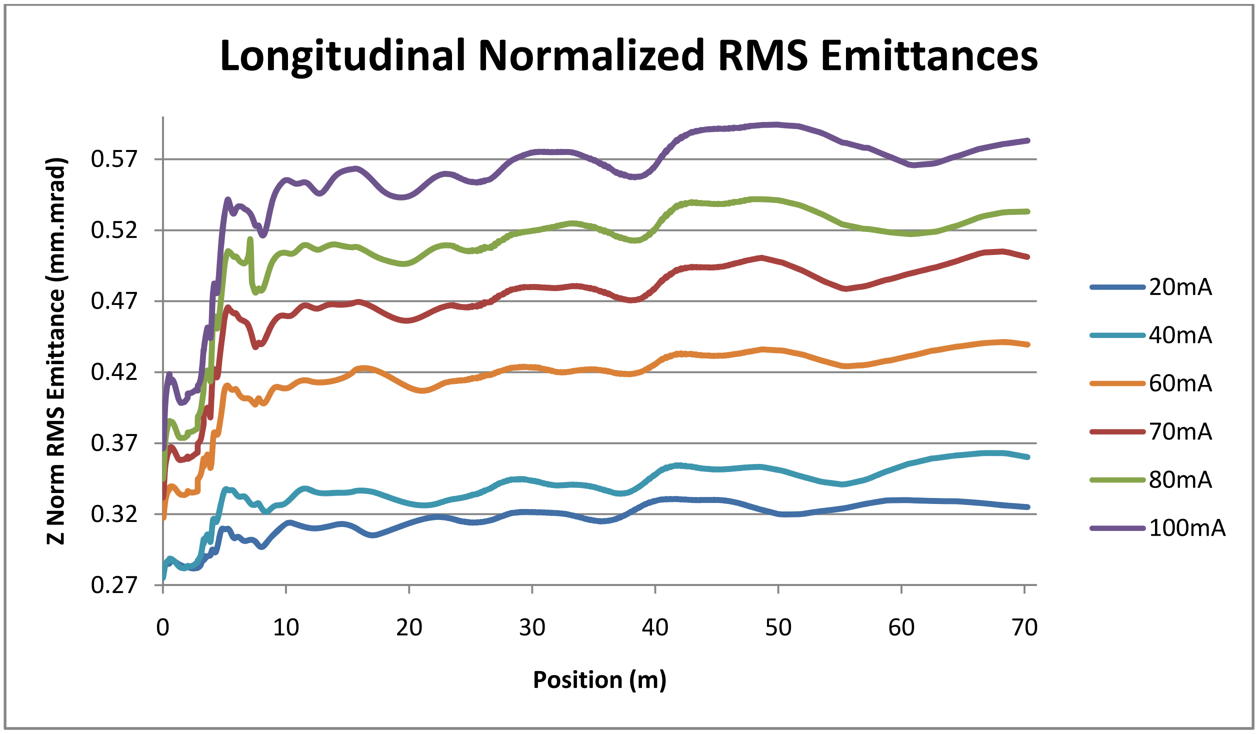

Figure10: Longitudinal emittance evolution from MEBT to PIMS.

The evolution of the emittances is very similar for all the cases and that higher the current, the higher the emittance increase. Concerning the low current cases, there is almost no emittance increase in transverse planes and it is very low in longitudinal.

Figure11 compiles the results for all the input currents all over the Linac4 structures. The ratio of the output current of each structure over the transverse emittance gives us an idea of the beam quality. This ratio cannot increase along the Linac or take a value above the reference. A decrease of this ratio can be explained by losses and/or emittance increase.

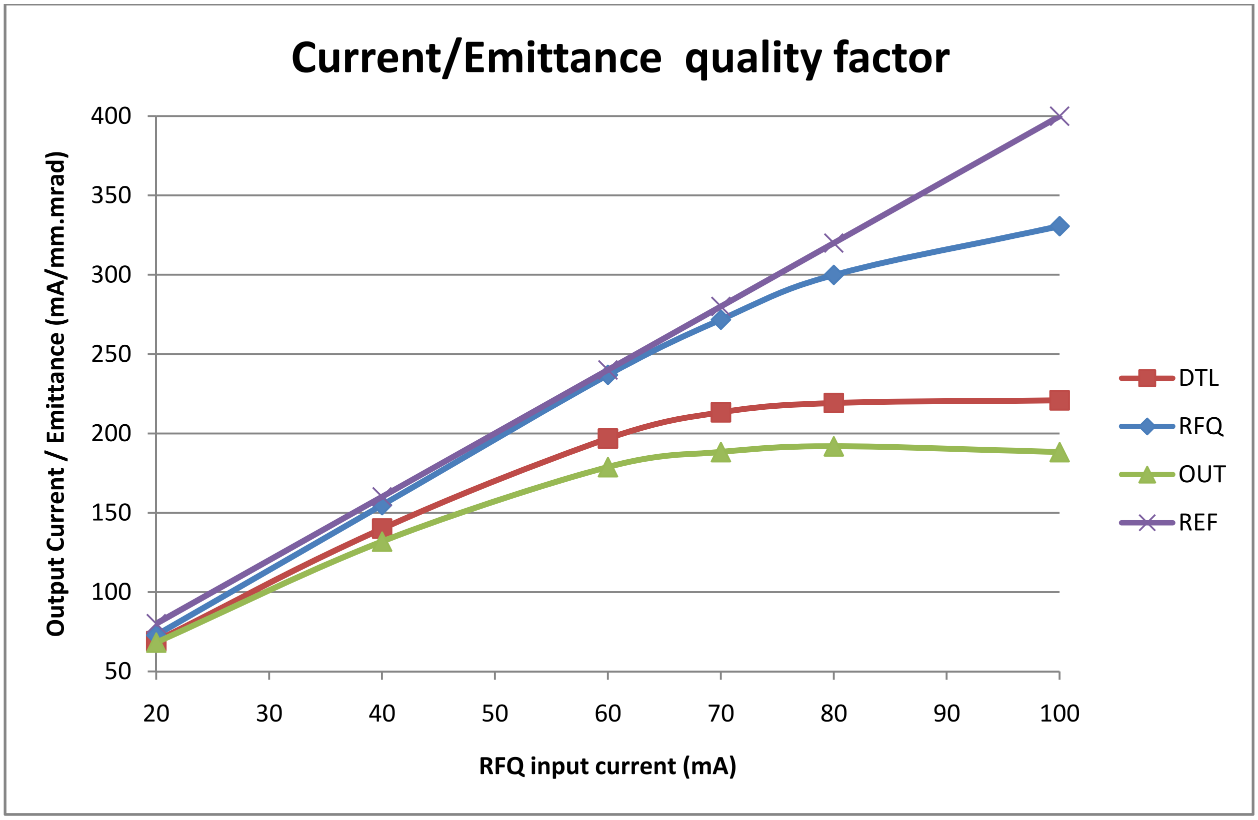

Figure11: Linac4 structures beam quality factor.

From this figure, we can find a summary of the results discussed previously. The evolution of the quality factor for the RFQ is linear and really close to the reference for the currents below 70-80mA. This tells us that for this range of current, the losses in RFQ are compensated by a decrease of the emittance. Above 80mA, it's not the case anymore. The losses become so important, that they cannot be balanced by an adjustment in emittance value. The chopper signature is really similar to the RFQ one. The factor is proportional until 70-80mA and starts to be degraded above 80mA. From 20 to 70mA, the difference between the RFQ beam quality factor and the chopper one is mainly due to the losses in the MEBT. Above 70mA, the emittance increase in the chopper-line is becoming quite high and adds to the losses to saturate the beam quality factor.

By looking at the evolution of beam quality factor at the Chopper and PIMS outputs, we can notice that the beam quality is almost not degraded along the path between the two structures. As there is no loss in the 70 meters of DTL, CCTL and PIMS, the slight beam degradation is only due the emittance increase.

We can then conclude that the Linac4 delivers a constant beam quality until 70-80mA (considering as acceptable a transmission of 90% from RFQ to PIMS). Above 80mA, we observe a saturation effect that over rides the advantages of increasing the source current.

In order to exclude the effects of the 3MeV part of the Linac on the beam in the downstream structures, we decided to regenerate the beams at the input of DTL. In Figure12 is represented the PIMS output beam quality factor evolution with input current. The reference is no more a straight line because we considered 20, 40, 60, 70, 80 and 100mA at the DTL input, but we took the emittance values from end-to-end.

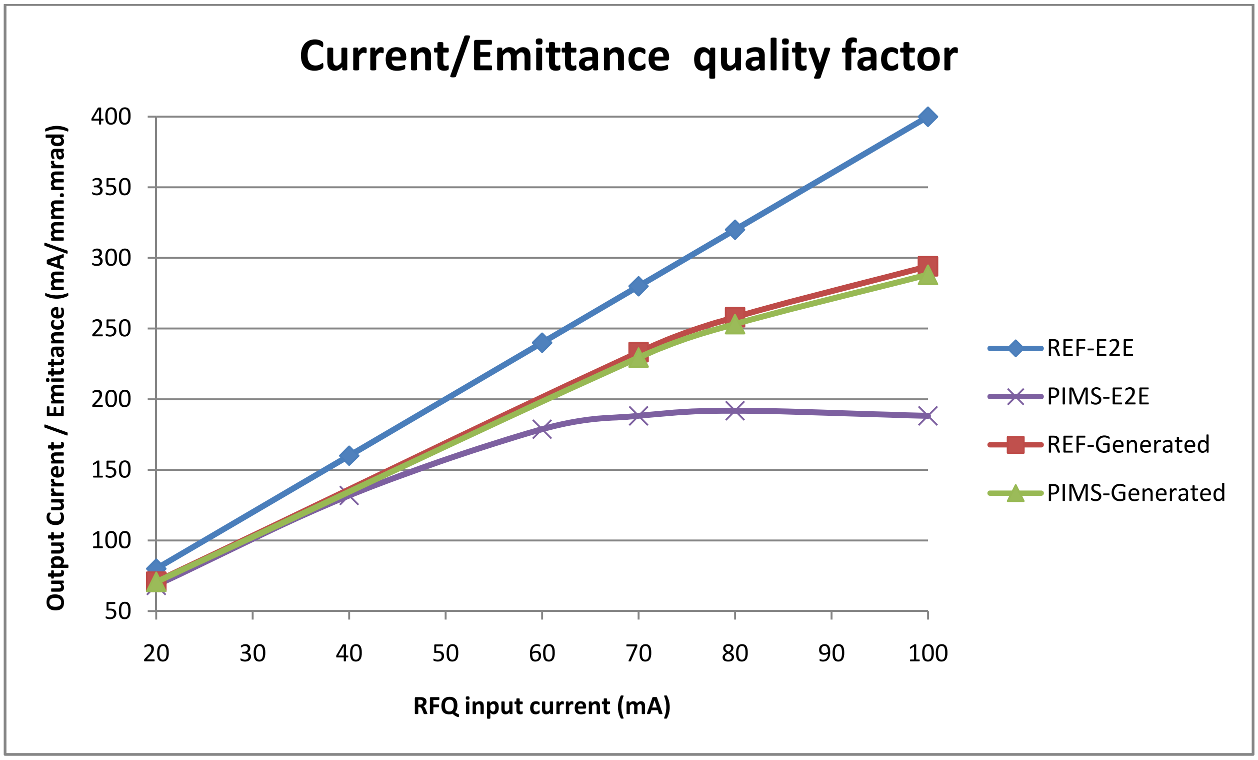

Figure12: DTL-CCDTL-PIMS beam quality factor.

This graph highlights that the beam is not degraded in the 3 to 160MeV part of the Linac if it does not come from the MEBT. The reference and the results of the simulations are really close and just differ by a very slight emittance increase for the high current cases (around 1%).

We can then conclude that the beam degradation observed in the DTL, CCDTL and PIMS for the end-to-end simulations are mainly amplification of beam quality degradation coming from the 3MeV part.

V Conclusions

This study showed that LINAC4 is capable to accelerate current from 0 to 100mA. All the main losses and emittance degradation happen before the beam reaches the DTL. It means that using permanent magnet quadrupoles in DTL and in CCDTL does not reduce the current acceptance. From the beam dynamics point of view, the bottleneck of Linac4 is the RFQ and the chopper-line, but it is the latter one that provides us the possibility of having a wide range of current in the downstream part of the Linac.

References

[1] K.R. Crandall et al., "RFQ design codes", LANL, LA-UR-96-1836, December 2005.

[2] R. Duperrier, "Toutatis, a radio-frequency quadrupole code", Phys. Rev, Spec. Top. Acc. & Beams, December 2000.

[3] R. Duperrier, N. Pichoff, D. Uriot, CEA Saclay codes review, ICCS Conference 2002, Amsterdam.