EU contract number RII3-CT-2003-506395 **CARE-Note-2007-010-HIPPI**

Comparative study of the beam dynamics in LINAC4 using CERN and RAL MEBT (Medium Energy Beam Transport) lines

C. Plostinar, STFC/RAL/ASTeC, Harwell, Didcot, Oxfordshire, UK
E. Sargsyan, CERN, Geneva, Switzerland

Abstract

This paper describes a simulation study of high intensity beam dynamics and beam transport when the RAL and CERN MEBT line designs are each fed into the same CERN LINAC4 structure. A comparative study of the efficiency of the two modes of operation has been made using two particle distributions: a uniformly generated beam at the input of the RFQ, and a more realistic beam generated at the LEBT input and tracked through the LEBT and the RFQ.

1. Introduction

CERN and RAL are working in parallel on the development of Front Ends for future particle accelerators: at CERN (European Organization for Nuclear Research) the Front End will be part of the LINAC4 [1], a potential replacement for LINAC2 accelerator, whilst at RAL (Rutherford Appleton Laboratory) the Front End is mainly intended to demonstrate that a high current, high quality chopped beam is achievable [2], making the RAL Front End a possible part of a Proton Driver for a future Neutrino Factory.

The two Front End designs have many similarities and consist of four main components: an H^- ion source, a Low Energy Beam Transport (LEBT) line to match the beam from the ion source into the RFQ (Radio-Frequency Quadrupole), an RFQ and a Medium Energy Beam Transport line with the beam chopper as seen in Figure 1.

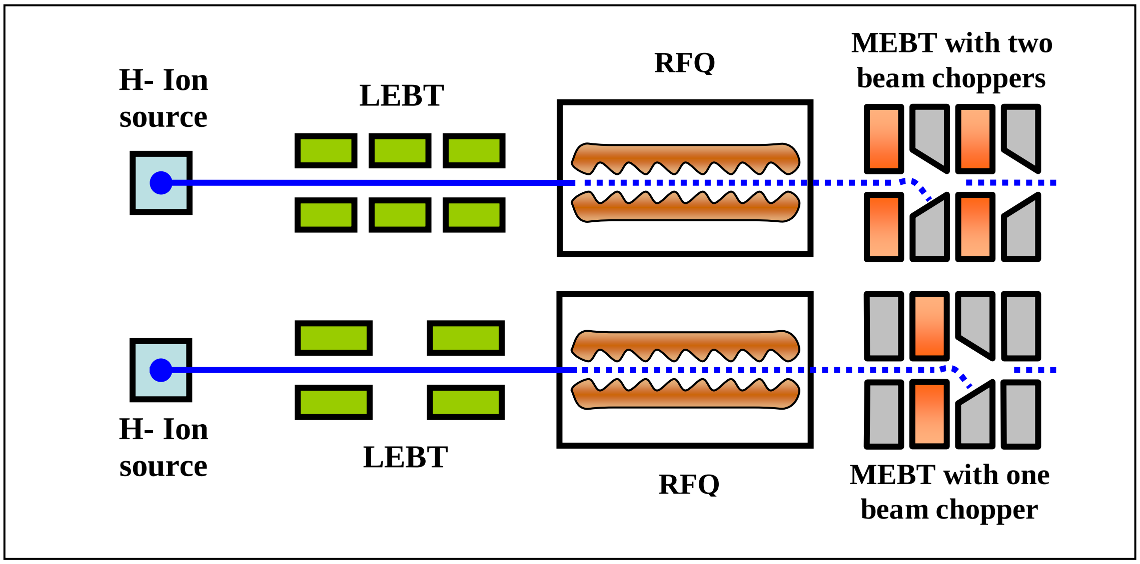


Figure 1: Schematic drawing of the Front End configuration for RAL (top) and CERN (bottom).

The MEBT chopper line is one of the key parts of these two Front End designs and it consists of a series of quadrupoles, RF re-bunching cavities, and a beam chopper system. While at CERN the MEBT optical design is final, at RAL three proposed designs are still under consideration: the symmetric scheme (Scheme A), the tandem scheme (Scheme B) and the compact scheme derived from the ESS chopper line (Scheme C) [3]. Figure 2 shows the RAL MEBT Scheme A and the CERN MEBT design.

CERN and RAL have adopted different approaches for their chopping schemes. The CERN design consists of a 1 meter long chopper (2 sets of plates each 40 cm long) housed inside two quadrupoles that are meant to keep the beam focused in the chopping plane and to provide a 90 degree phase advance between the centre of the chopper and the beam dump. In order to obtain nanosecond range rise times, the CERN deflecting plates are made using travelling-wave stripline structures that are meander-folded in order to match the speed of the travelling wave to the beam velocity [4]. A summary of the CERN and RAL MEBT parameters can be seen in Table 1 and 2 respectively. The RAL chopper uses a configuration first developed for the ESS (European Spallation Source), and consists of a tandem combination of fast transition time, short duration and slower transition time, longer duration choppers (the 'fast-slow' beam choppers). The "fast-chopper" removes 3 adjacent bunches at the beginning and at the end of the chopping interval creating 2 gaps in the bunch train. These gaps will then be used by the second chopper field as a transition interval. This prevents bunches being partially chopped during the transition time of the second chopper [5].

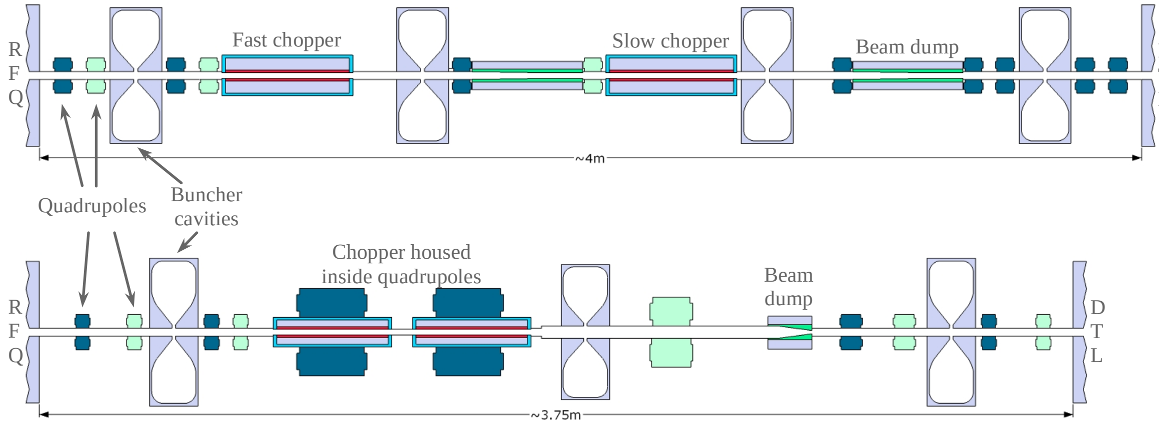


Figure 2: Schematic drawing of the RAL MEBT Scheme A (top) and the CERN MEBT Line (bottom).

Table 1: CERN MEBT elements.

Element type	**Number**	**Length [mm]**	**Value**
Long Quadrupole I	2	255	G = 0.6 – 1.7 T/m
Long Quadrupole II	1	155	G = 4.3 T/m
Short Quadrupole I	6	56	G = 15 – 38 T/m
Short Quadrupole II	2	82	G = 11 – 12 T/m
Buncher cavities	3	200	V = 100 – 140 kV
Chopper	2 plates	400	V = +/- 0.5 kV
Beam dump	1	200 (120 effective length)	–

Table 2: RAL MEBT elements.

Element type	**Number**	**Length [mm]**	**Value**
Quadrupole	11	70	G = 9 – 33 T/m
Buncher cavities	4	200	V = 75 – 160 kV
Fast chopper	1	450	V = +/- 1.4 kV
Slow chopper	1	450	V = +/- 1.7 kV
Beam dump	2	400	–

2. Simulation results

The purpose of this work was to simulate the RAL Scheme A and CERN MEBT designs on the CERN LINAC4 design that consists of a Drift Tube Linac (DTL) followed by a Cell-Coupled Drift Tube Linac (CCDTL) and a Side-Coupled Linac (SCL) [6], and do a comparative study of the two different chopping approaches (CERN and RAL). Since the two Front Ends have been designed for different frequencies (324 MHz for RAL and 352.2 for CERN), the RAL design had to be scaled to the new frequency to enable a better comparison, by considering a higher frequency for the buncher cavities. All the simulations have been performed with TraceWin/Partran [7] with 3D space-charge routines, using two beam distributions: a uniformly generated beam at the input of the IPHI RFQ [8] and a beam tracked through the LEBT and the RFQ.

2.1 Input distribution: Uniformly generated beam at the RFQ input.

The overall efficiency of the two structures can be compared in terms of losses, RMS emittance growth, and halo development. The input parameters for this distribution are given in Tables 3 and 4 and in Figure 3.

Table 3: RAL Scheme A & CERN input parameters.

	RAL Scheme A & CERN MEBT
Beam Current	70 mA
Bunch frequency	352.2 MHz
Kinetic Energy	3 MeV
Number of particles	50000
Particle Distribution	Generated Uniform Distribution at the input of the RFQ

Table 4: Input Emittances and Twiss Parameters for the two structures.

X-X'	**Y-Y'**
E [rms] = 0.2733 Pi.mm.mrad [Norm] E [90%] = 1.1433 Pi.mm.mrad [Norm] β = 0.2041 mm/Pi.mrad α = 0.9615	E [rms] = 0.2710 Pi.mm.mrad [Norm] E [90%] = 1.1335 Pi.mm.mrad [Norm] β = 0.4347 mm/Pi.mrad α = -1.6637
Phase-Energy	**Z-Z'**
E [rms] = 0.1357 Pi.deg.MeV [Norm] E [90%] = 0.6352 Pi.deg.MeV [Norm] β = 594.7093 deg/Pi.MeV α = 0.2638	E [rms] = 0.3416 Pi.mm.mrad [Norm] E [90%] = 1.5989 Pi.mm.mrad [Norm] β = 0.6824 mm/Pi.mrad α = -0.2638
Mo = 939.294308 MeV	Beta = 0.0799867 Gamma = 1.0032144

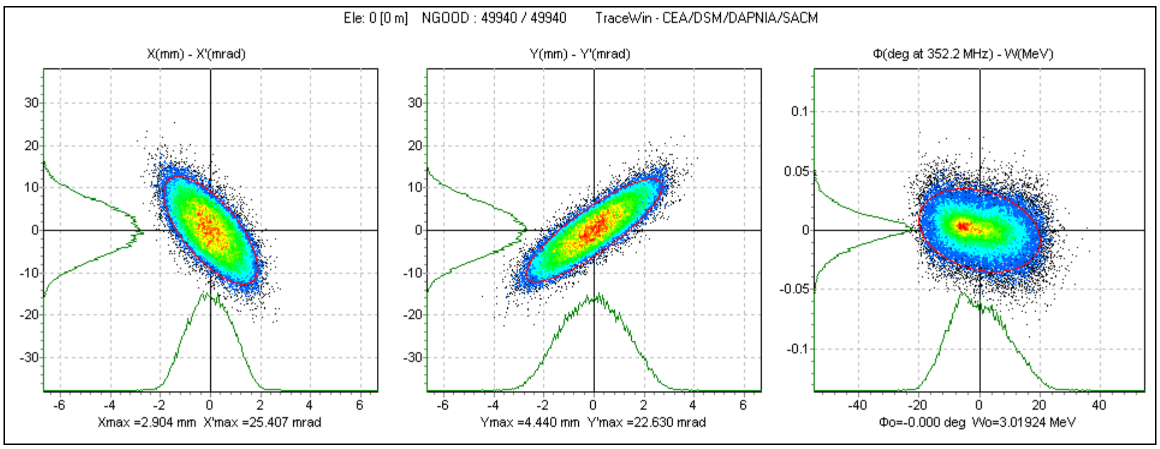


Figure 3: MEBT Input distribution (Uniform Distribution at the RFQ input).

These particles are then tracked through the CERN and RAL MEBT lines. As described above, the choppers are quite long objects and by placing them in the MEBT beam lines, the phase advance per meter is considerably modified; for this reason the quadrupoles in the MEBT line are arranged so that in both designs they form FODO focusing periods. In this way the continuity of the phase advance is modified as little as possible.

Some of the quadrupoles are also used to amplify the deflection given by the choppers, thus reducing the required voltage on the chopper plates. Table 5 shows the beam parameters out of the MEBT for RAL and CERN schemes. The transverse and longitudinal 5 RMS envelopes for the MEBT line can be seen in Figure 5. For these simulations the beam choppers are switched off.

Table 5: MEBT output Emittances and Twiss Parameters for the two schemes.

Emittance [norm]	RAL Scheme A	CERN
X-X'	E [rms] = 0.2811 Pi.mm.mrad E [90%] = 1.1844 Pi.mm.mrad β = 0.6222 mm/Pi.mrad α = 5.2151	E [rms] = 0.3066 Pi.mm.mrad E [90%] = 1.3168 Pi.mm.mrad β = 0.6016 mm/Pi.mrad α = 4.9432
Y-Y'	E [rms] = 0.2979 Pi.mm.mrad E [90%] = 1.2695 Pi.mm.mrad β = 0.1473 mm/Pi.mrad α = -1.7106	E [rms] = 0.2874 Pi.mm.mrad E [90%] = 1.2732 Pi.mm.mrad β = 0.1513 mm/Pi.mrad α = -2.0002
Z-Z'	E [rms] = 0.3418 Pi.mm.mrad E [90%] = 1.5684 Pi.mm.mrad β = 0.3431 mm/Pi.mrad α = 0.0657	E [rms] = 0.3745 Pi.mm.mrad E [90%] = 1.7301 Pi.mm.mrad β = 0.3620 mm/Pi.mrad α = -0.0779
Phase-Energy	E [rms] = 0.1358 Pi.deg.MeV E [90%] = 0.6231 Pi.deg.MeV β = 299.0289 deg/Pi.MeV α = -0.0657	E [rms] = 0.1488 Pi.deg.MeV E [90%] = 0.6873 Pi.deg.MeV β = 315.4377 deg/Pi.MeV α = 0.0779

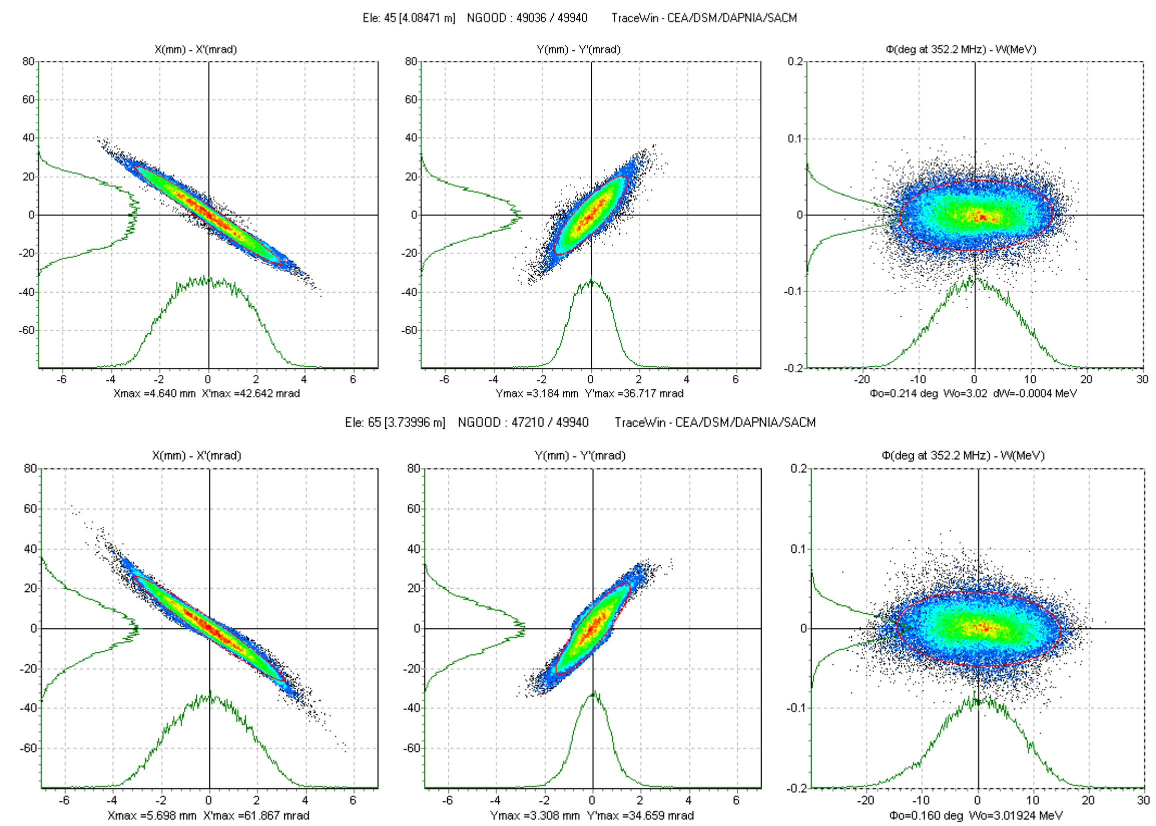


Figure 4: MEBT output distribution for RAL MEBT Scheme A (top) and CERN MEBT (bottom).

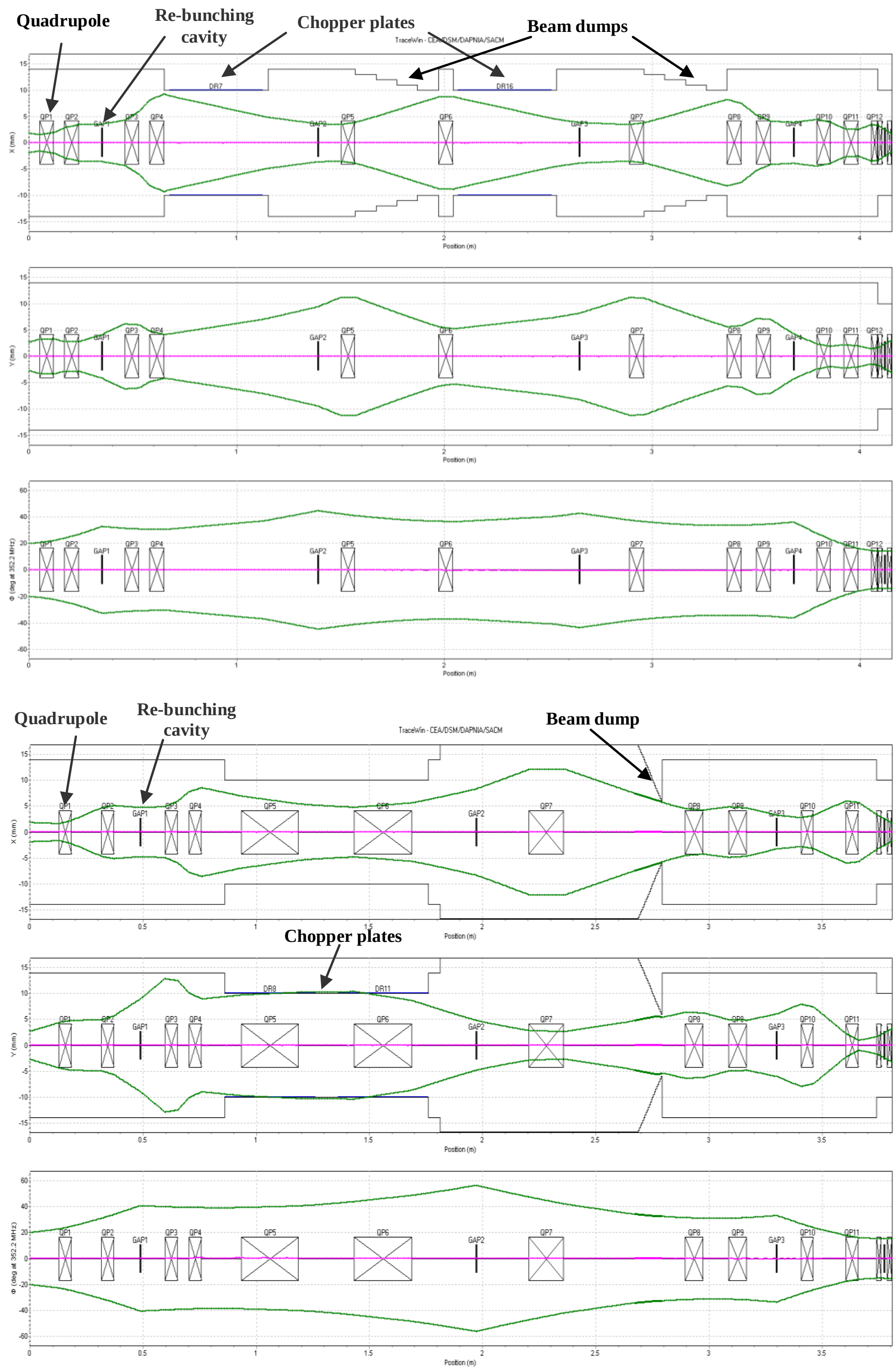


Figure 5: MEBT Beam Envelopes (from Partran, 5 RMS) for RAL Scheme A (top) and CERN (bottom) with chopper off.

For the RAL MEBT the matching to the DTL was made using the last 5 quadrupoles and the last re-bunching cavity. One extra focusing quadrupole was added so that the last quadrupole had the right polarity for matching to the DTL. Although the matching is not perfect, it is still within reasonable limits for the purpose of this simulation (maximum 5% mismatch). The CERN MEBT matching is done with the last four quadrupoles and the last re-bunching cavity. The Linac itself accelerates the beam from 3 MeV to 160 MeV using 3 different accelerating structures: DTL up to 40 MeV where a more efficient CCDTL structure is used to accelerate the beam to 90 MeV where the frequency is doubled and the accelerating structure is changed to a SCL. The LINAC4 output beam parameters can be seen in the Table 6 and Figures 6-10.

Table 6: LINAC4 output emittances and Twiss Parameters for the two schemes.

Emittance [norm]	**RAL Scheme A**	**CERN**
X-X'	E [rms] = 0.3133 Pi.mm.mrad E [90%] = 1.3069 Pi.mm.mrad β = 9.8174 mm/Pi.mrad α = 3.7172	E [rms] = 0.3259 Pi.mm.mrad E [90%] = 1.4059 Pi.mm.mrad β = 8.9570 mm/Pi.mrad α = 3.4777
Y-Y'	E [rms] = 0.3152 Pi.mm.mrad E [90%] = 1.3288 Pi.mm.mrad β = 3.7839 mm/Pi.mrad α = -1.5	E [rms] = 0.3240 Pi.mm.mrad E [90%] = 1.3842 Pi.mm.mrad β = 3.2614 mm/Pi.mrad α = -1.2915
Z-Z'	E [rms] = 0.3964 Pi.mm.mrad E [90%] = 1.8013 Pi.mm.mrad β = 7.5742 mm/Pi.mrad α = -0.0760	E [rms] = 0.4107 Pi.mm.mrad E [90%] = 1.8361 Pi.mm.mrad β = 7.3631 mm/Pi.mrad α = -0.0342
Phase-Energy	E [rms] = 0.1575 Pi.deg.MeV E [90%] = 0.7156 Pi.deg.MeV β = 14.7041 deg/Pi.MeV α = 0.076	E [rms] = 0.1632 Pi.deg.MeV E [90%] = 0.6873 Pi.deg.MeV β = 315.4377 deg/Pi.MeV α = 0.0779

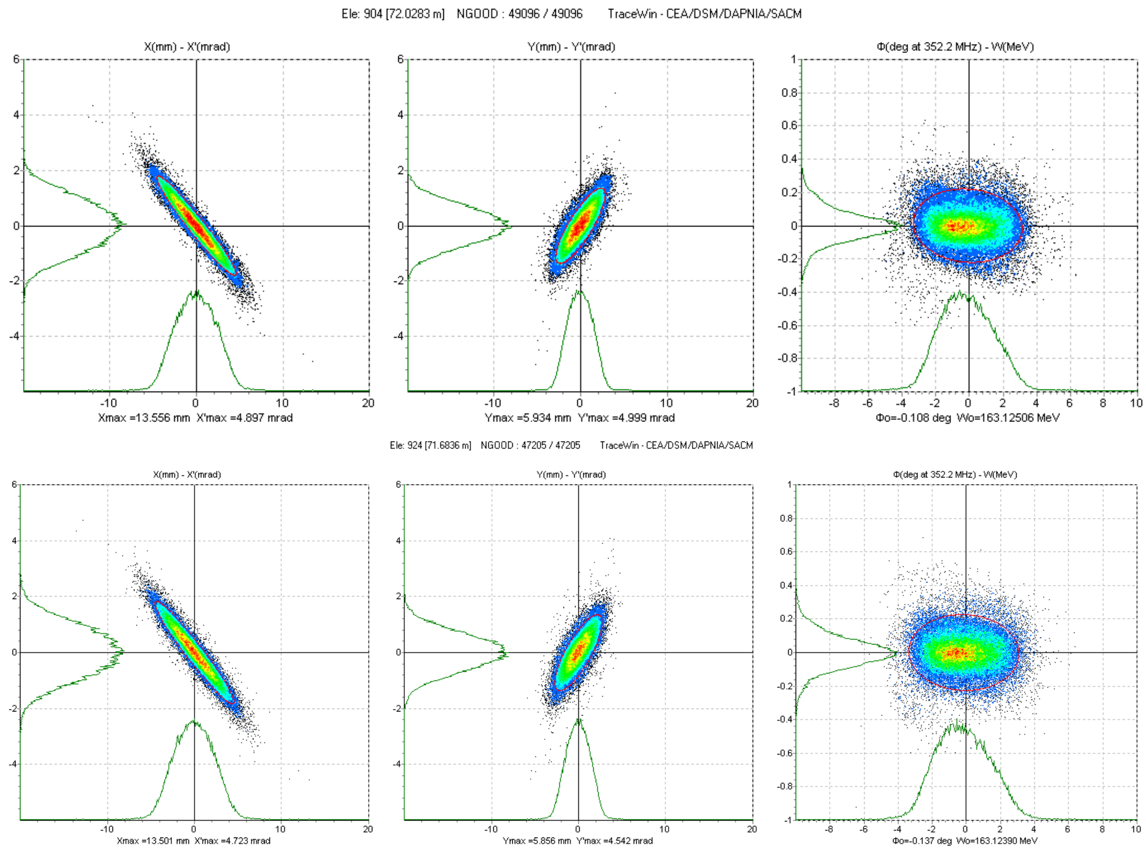


Figure 6: LINAC4 output distribution with RAL MEBT Scheme A (top) and CERN MEBT (bottom).

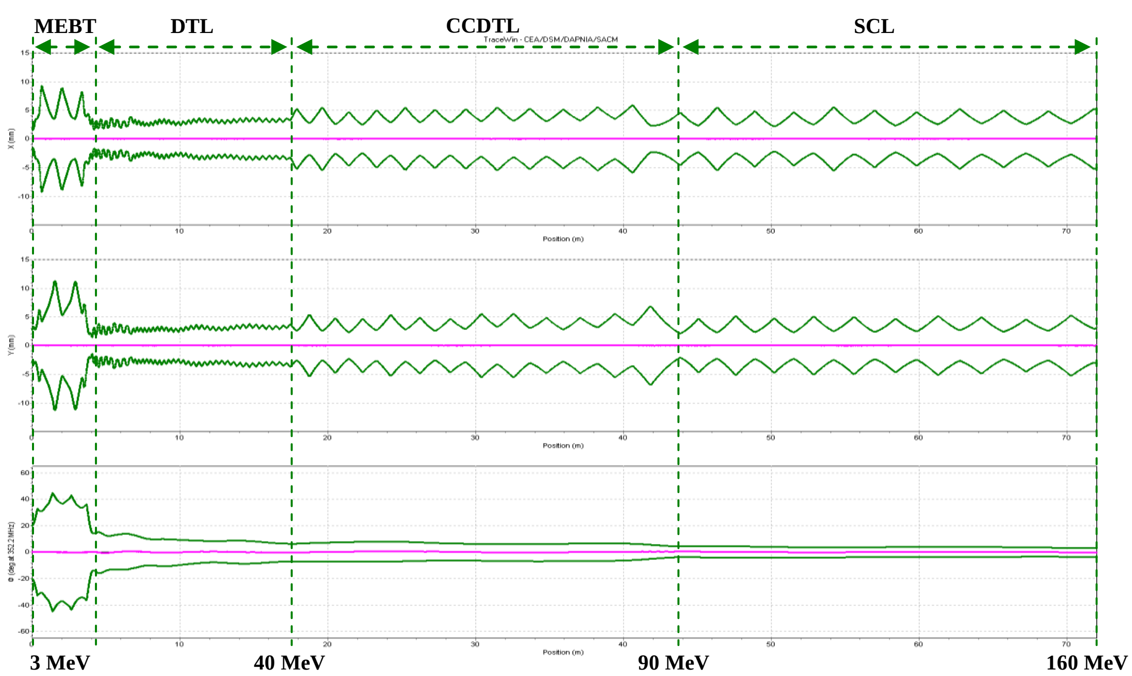


Figure 7: RAL MEBT + LINAC4 Beam Envelopes (from Partran, 5 RMS).

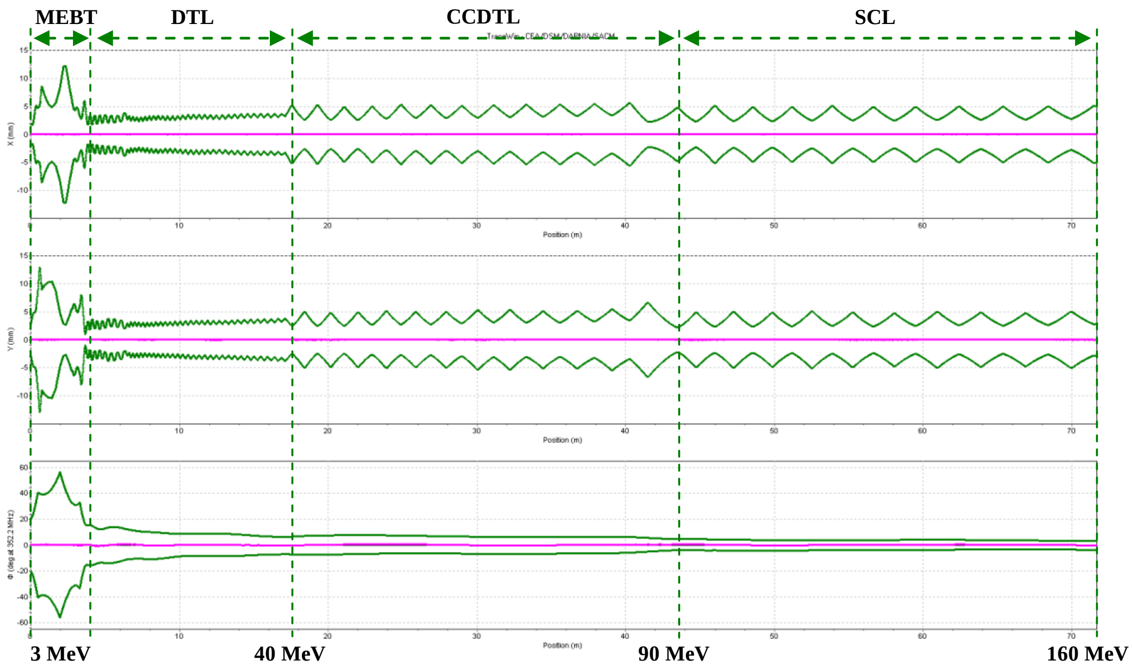


Figure 8: CERN MEBT + LINAC4 Beam Envelopes (from Partran, 5 RMS).

The transverse and longitudinal normalized RMS emittances evolution in the MEBT and LIANC 4 is presented in figures 9 and 10.

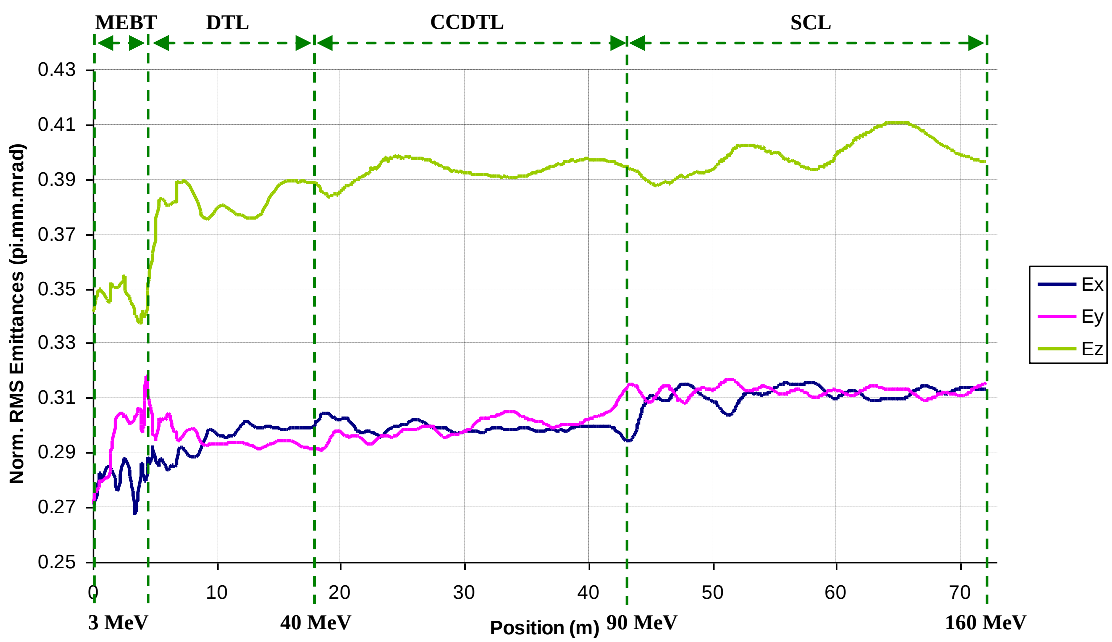


Figure 9: RAL MEBT + LINAC4 Longitudinal and Transverse Emittances evolution (Normalized RMS).

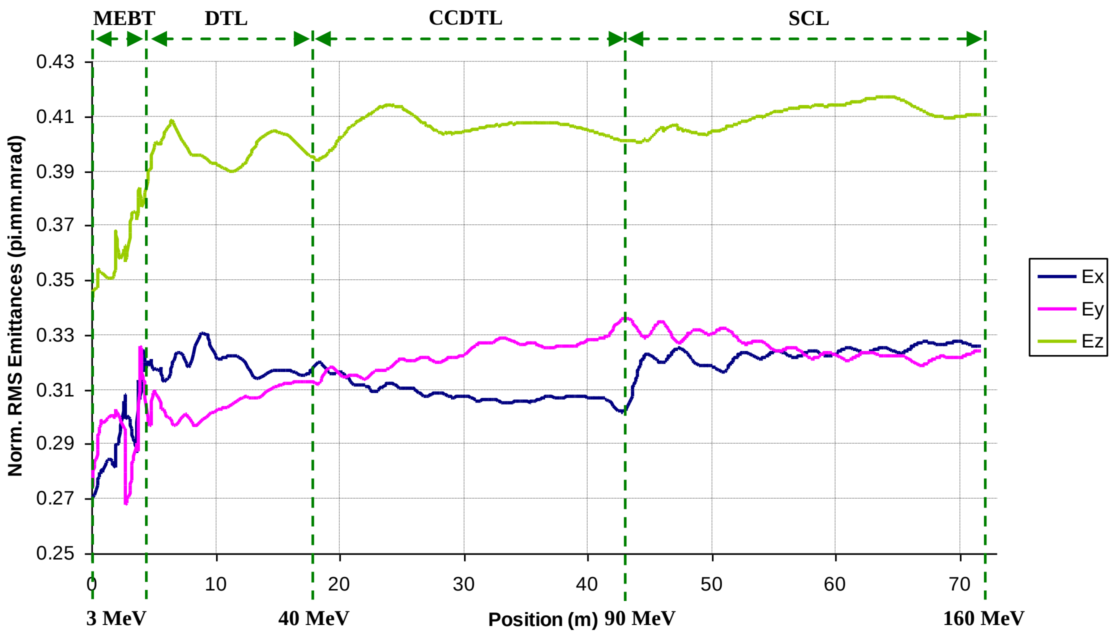


Figure 10: CERN MEBT + LINAC4 Longitudinal and Transverse Emittances evolution (Normalized RMS).

Table 7: RMS Emittance growth and beam transmission (RAL Scheme A).

	ε_x growth (%)	**ε_y growth (%)**	**ε_z growth (%)**	**Transmission (%)**
MEBT	2.85	9.92	0.05	98.31
LINAC4	11.45	5.80	15.97	100
TOTAL	14.63	16.30	16.05	98.31

Table 8: RMS Emittance growth and beam transmission (CERN Scheme).

	ε_x growth (%)	**ε_y growth (%)**	**ε_z growth (%)**	**Transmission (%)**
MEBT	12.18	6.05	9.63	94.55
LINAC4	6.30	12.73	9.66	100
TOTAL	19.25	19.55	20.25	94.55

The RMS emittance increase and the beam transmission for RAL and CERN schemes are shown in tables 7 and 8. For the RAL case the growth in emittance is lower than in the CERN case. Emittances at the output of the CERN MEBT are already bigger than in the RAL case due to the fact that the CERN design has more constraints regarding the beam optics. Consequently, this difference is more or less preserved in the linac, hence the difference in the total emittance growth.

It is important to avoid emittance growth in the transverse plane since the bore radius in the LINAC4 is quite small and emittance growth can cause a beam loss. An important source of emittance growth is the emittance exchange between the longitudinal and the transverse planes. However, simulations indicate that the linac has been designed to avoid the unstable are of the Hofmann’s instability chart [9], so that resonances are avoided in both cases. However, there are a few points in the linac where resonances are crossed, but for a very short period, with almost no effect on the beam.

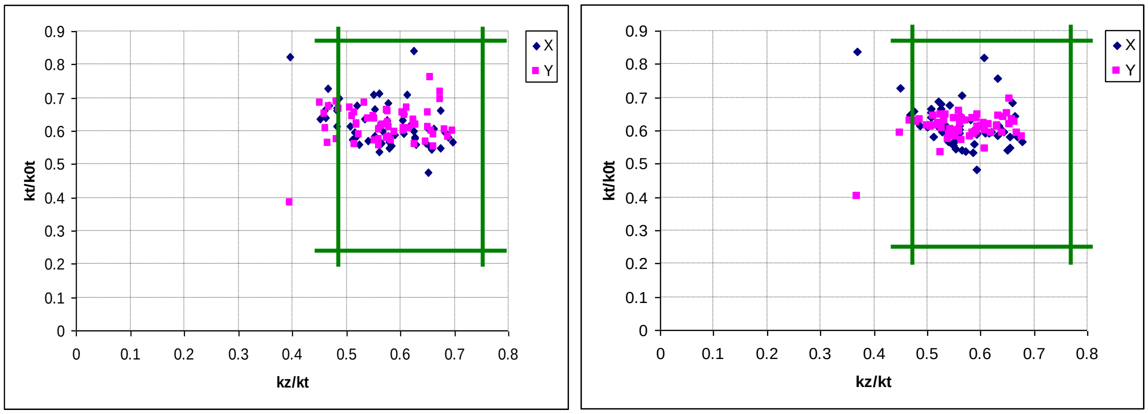


Figure 11: Stable region in Hofmann's instability plot (green rectangle). RAL Scheme A (Left) and CERN (Right).

Halo formation [10] is an important source of emittance growth that can lead to beam loss and radio activation of the linac, a process that has to be avoided in high intensity linacs. To reduce the halo, scrapers have been included at key positions in the LINAC4 design but not in these simulations. This allows us to observe the halo development along the linac as it can be seen in figures 12 and 13.

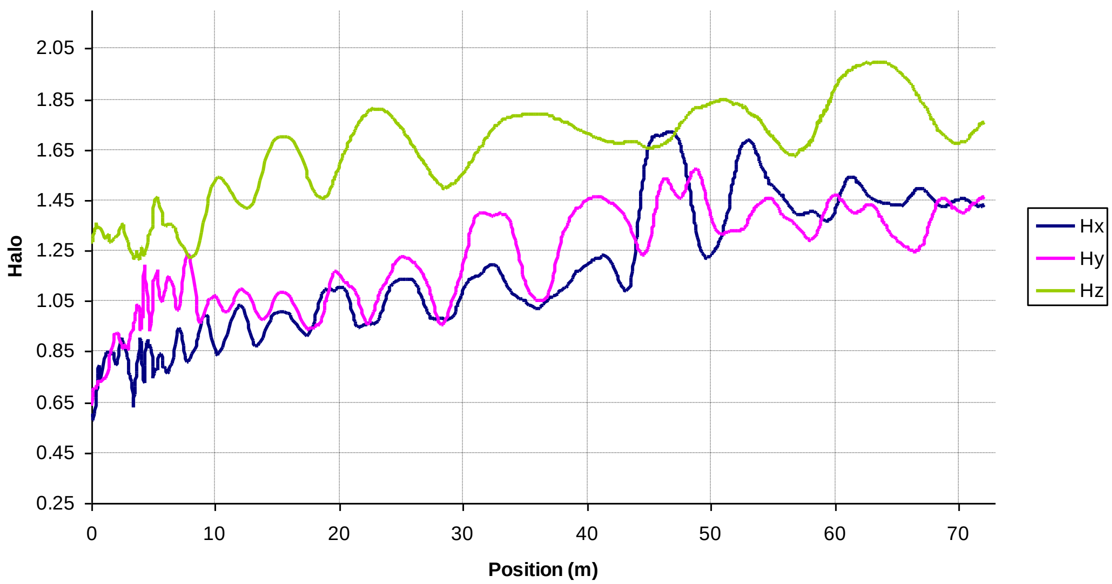


Figure 12: Halo development (RAL Scheme A).

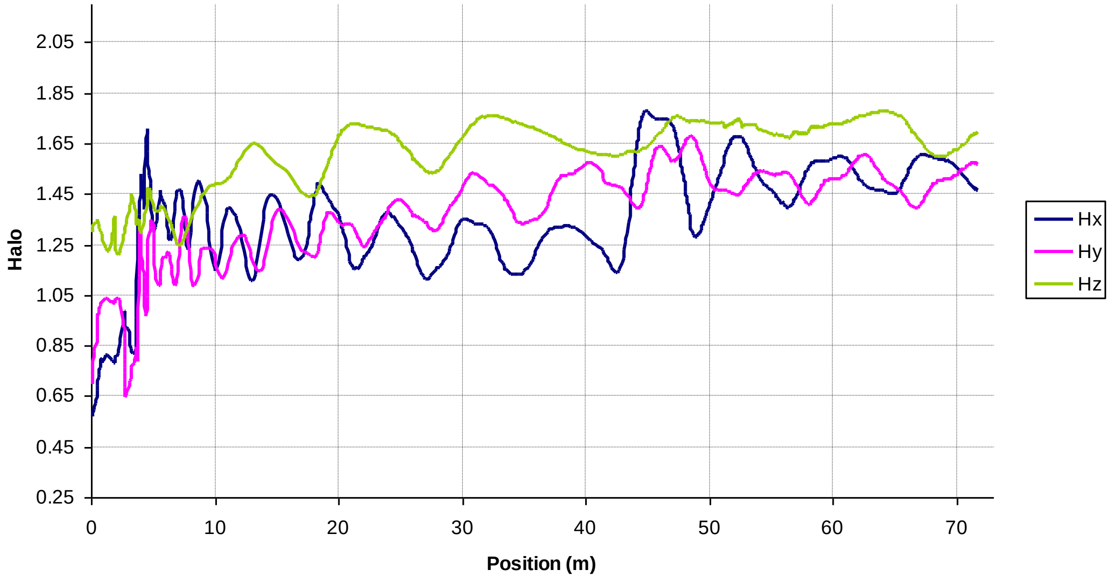
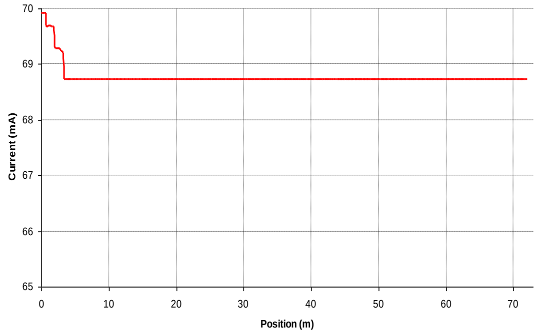


Figure 13: Halo development (CERN).

Plots 14 - 16 present the current variation and the losses at each position in the MEBT and linac. While almost no losses occur on the accelerating structures, the MEBT line is quite lossy for both designs. For the RAL design some particles are lost on the beam dumps. These losses can be reduced by increasing the aperture at the dump, but for this, one would need a stronger deflection from the chopper plates, and hence a higher voltage. For the CERN design, losses are higher and occur mainly on the chopper plates and on the beam dump/scraper, where quite a considerable amount of power is dissipated on a small volume, making the dump one of the "hottest points" in the linac. The aperture of the CERN MEBT beam dump is made intentionally smaller so that it can be used as a scraper. Designs with higher aperture can be considered, provided a higher voltage on the chopper plates is achievable, but they could be used only for dumping the beam and the beneficial effect of reducing the halo would be lost.



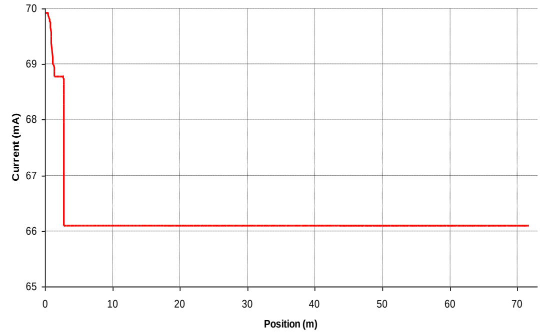


Figure 14: Current variation. RAL Scheme A (Left) and CERN (Right).

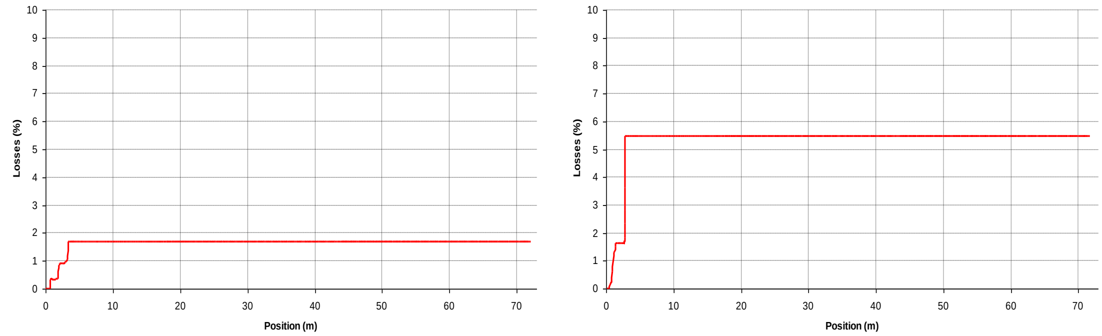


Figure 15: Losses (%) RAL Scheme A (Left) and CERN (Right).

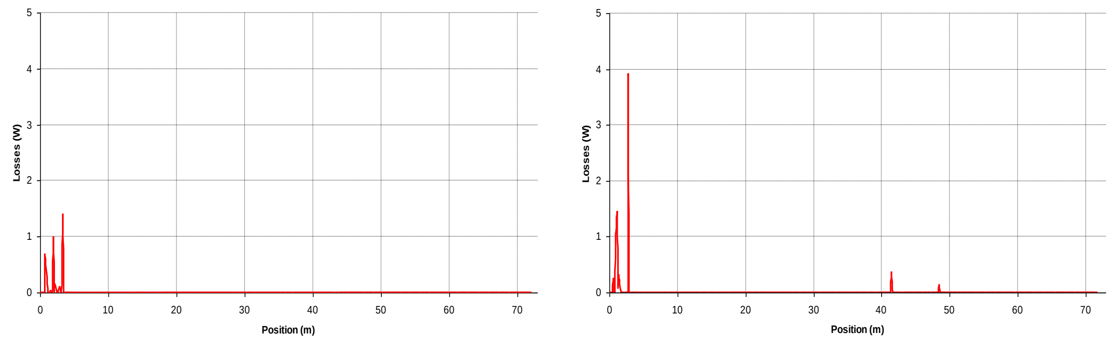


Figure 16: Losses (W) for a 0.1% duty cycle. RAL Scheme A (Left) and CERN (Right).

2.2 Input distribution: Beam tracked through the LEBT and the RFQ

The second beam distribution used was a beam already tracked through the LEBT and the RFQ which has the advantage of being more realistic [11]. The basic input parameters can be seen in Table 9. The beam dynamics in this case is very similar to the case when the uniform RFQ distribution was used. The main difference is the particle loss which as expected is higher, due to bigger input emittances (See Figures 18, 19 and 20). The emittance growth is lower for both cases, primarily due to two factors: the input MEBT emittances are already higher to start with and secondly, the beam loss in the MEBT line is more significant than in the previous case.

Table 9: Input beam parameters.

	RAL Scheme A & CERN MEBT
Beam Current	70 mA
Bunch frequency	352.2 MHz
Kinetic Energy	3 MeV
Number of particles	49500
Particle Distribution	Beam tracked through the LEBT and the RFQ
Input RMS Emittances	ε_x=0.3102, ε_y=0.3096, ε_z=0.3814

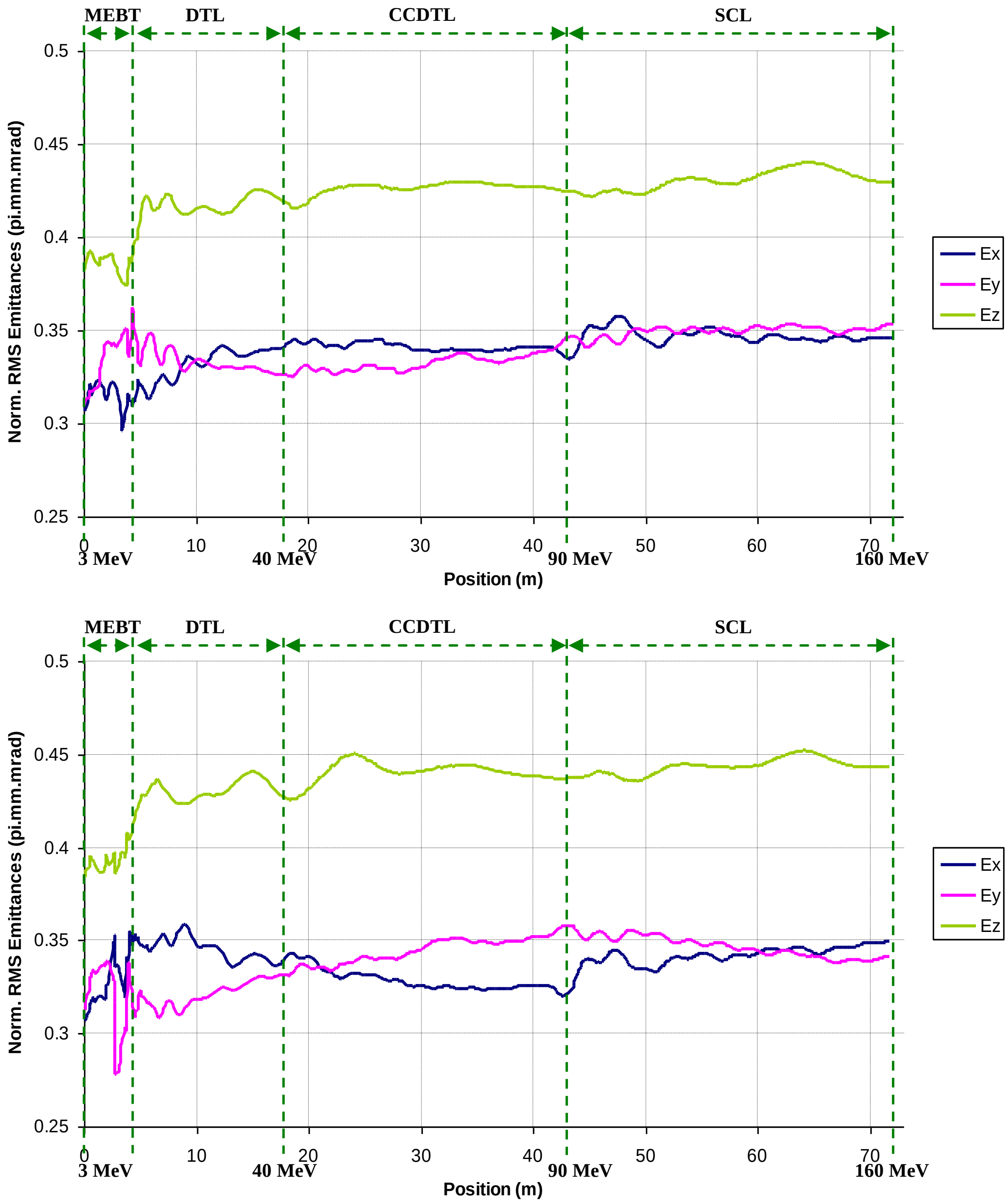


Figure 17: Longitudinal and Transverse Emittances evolution (Normalized RMS), for the RAL case (top) and the CERN case (bottom).

Table 10: RMS Emittance growth and beam transmission (RAL Scheme A).

	ε_x growth (%)	ε_y growth (%)	ε_z growth (%)	Transmission (%)
MEBT	0.61	8.75	1.91	97.17
LINAC4	10.92	5.05	10.40	100
TOTAL	11.60	14.24	12.50	97.17

Table 11: RMS Emittance growth and beam transmission (CERN Scheme).

	ε_x growth (%)	ε_y growth (%)	ε_z growth (%)	Transmission (%)
MEBT	8.12	-2.80	4.37	91.25
LINAC4	4.23	13.32	11.35	100
TOTAL	12.70	10.14	16.20	91.25

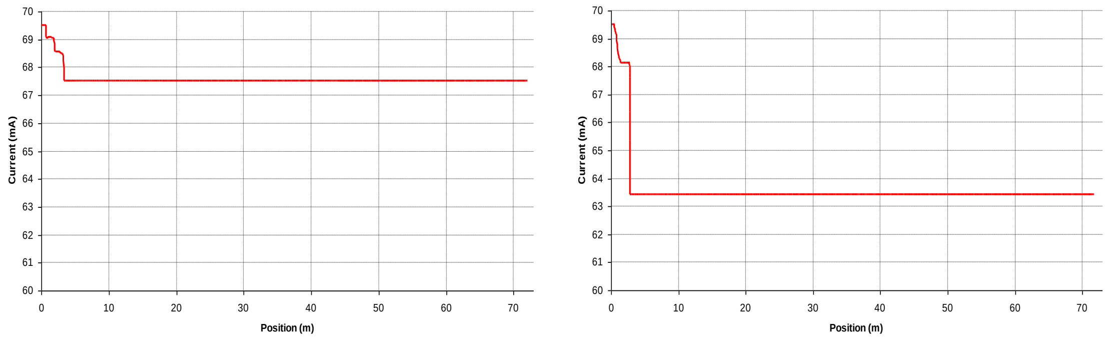


Figure 18: Current variation. RAL Scheme A (Left) and CERN (Right).

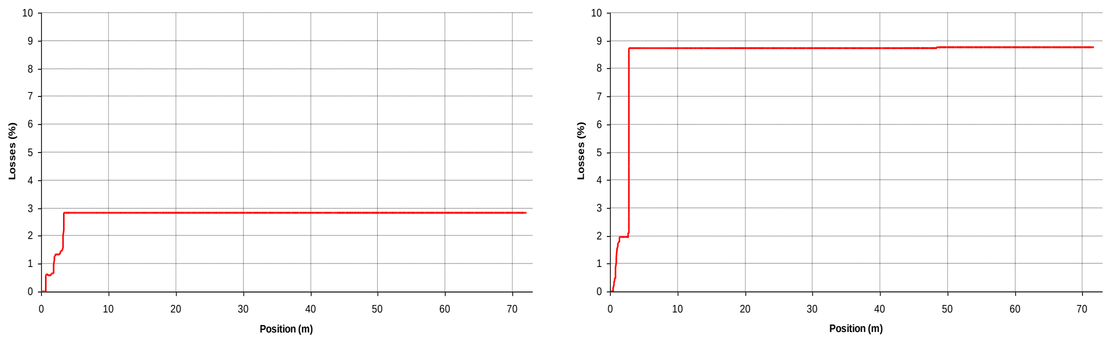


Figure 19: Losses (%) RAL Scheme A (Left) and CERN (Right).

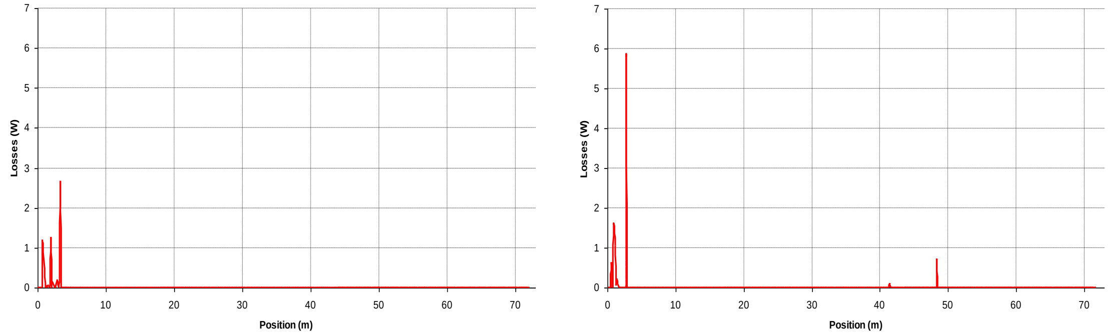


Figure 20: Losses (W) for a 0.1% duty cycle. RAL Scheme A (Left) and CERN (Right).

3. Residual chopped beam simulations.

For the CERN MEBT design the voltage on the chopper plates is limited to 500 V. Most of the chopped beam is lost on the beam dump (99.88 %), but a small fraction of the beam will remain and will continue in the downstream linac. This can be quite problematic especially if the unchopped particles survive and are subsequently accelerated to higher energies.

For the RAL chopper, higher voltages can be applied on the plates thus the chopping efficiency can be even higher. With TraceWin we have performed the simulations considering one of the choppers alternately switched off. With the slow chopper off, a voltage of 1300V on the fast chopper will deflect 99.87% of the beam. Approximately 50% of the remaining unchopped beam will be lost in the remaining part of the MEBT, mainly on the second beam dump, so that at the MEBT output almost 100% of the chopped beam will be lost. The remaining beam will be injected into the linac where scrapers (already in the LINAC4 design, but not included in this simulation) must be placed in order to avoid the propagation of the unchopped particles even further downstream. In the RAL MEBT design, the residual beam from the fast chopper will also receive a deflection from the rising field of the slow chopper, with a positive effect on the chopping efficiency. The beam power dissipated by the unchopped particles is about 1W on each different accelerating structure (DTL, CCDTL, SCL) for both CERN and RAL designs. The beam envelopes in the MEBT line when the choppers are on can be seen in Figure 21 and a summary of the chopping efficiency is given in Table 12 where scenarios with a reduced chopper voltage have been considered.

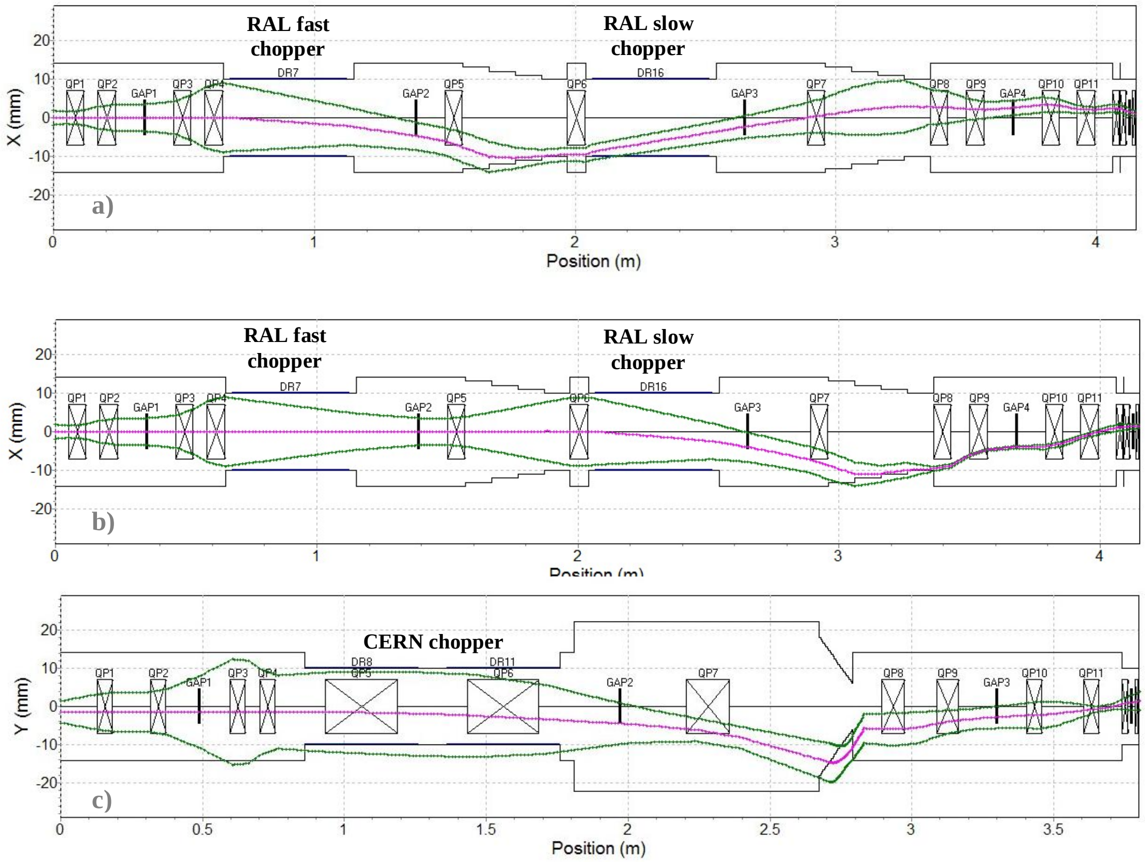


Figure 21: Beam envelopes in the MEBT line (5 RMS): RAL Fast Chopper on (a), RAL slow chopper on (b), CERN chopper on (c).

Table 12: Residual Chopped Beam for a uniform distribution generated at the RFQ input.

	CERN	RAL Scheme A			
	Chopper	Fast Chopper	After the MEBT	Slow Chopper	After the MEBT
Voltage	500 V	1300 V	-	1500 V	-
Chopped beam	99.88 %	99.87 %	99.94 %	99.96 %	99.96 %
Chopped beam with 5% voltage drop	99.78 %	99.52 %	99.67 %	99.90 %	99.90 %
Chopped beam with 10% voltage drop	99.64 %	98.66 %	99.01 %	99.77 %	99.77 %
Dissipated power on the dump	~ 210 W (0.1% DC)				
	~ 6.3 kW (3% DC)				

4. Conclusions

Although CERN and RAL have adopted different chopping schemes, end-to-end simulations indicate that they are similar in many respects. Slightly better results have been obtained when using the RAL chopper line, mainly due to the different MEBT optics in the two cases. The CERN MEBT line is already in a more advanced design stage, whereas for the RAL case more realistic engineering considerations have yet to be added in with expected influence on the beam dynamics. Simulations made with the two different beam distributions show that LINAC4 has been designed to be a stable and reliable machine, and that the differences in the beam dynamics in the linac are mainly caused by the differences in the MEBT line optics.

5. Acknowledgments

We acknowledge the support of the European Community-Research Infrastructure Activity under the FP6 “Structuring the European Research Area” program (CARE, contract number RII3-CT-2003-506395).

6. Refferences.

[1] R. Garoby et al., “Design of LINAC4, a New Injector for the CERN Booster”, Proc of Linac 2004, Lübeck, Germany, August 2004.

[2] A. Letchford et al., “The RAL Front End Test Stand”, Proc. of EPAC 2006, Edinburgh, Scotland, June 2006.

[3] M. Clarke-Gayther et al., “A Fast Beam Chopper for the RAL Front End Test Stand”, Proc. of EPAC 2006, Edinburgh, Scotland, June 2006.

[4] F. Caspers et al., “The CERN-SPL Chopper Concept and Final Layout”, Proc. Of EPAC 2004, Lucerne, Switzerland, July 2004.

[5] M. Clarke-Gayther, “A Fast Beam Chopper for Next Generation High Power Proton Drivers”, Proc. Of EPAC 2004, Lucerne, Switzerland, July 2004.

[6] F Gerigk et al., “Conceptual Design of the SPL II”, CERN-2006-006 report, Geneva, Switzerland, July, 2006.

[7] N. Pichoff, D. Uriot, "PARTRAN," Internal Memorandum, CEA, Saclay.

[8] P-Y. Beauvais, “Recent Evolutions in the Design of the French High Intensity Proton Injector (IPHI)”, Proc. Of EPAC 2004, Lucerne, Switzerland, July 2004.

[9] I. Hofmann, “Stability of Anisotropic Beams with Space Charge”, Physical Review E 57, 4713, 1998.

[10] C. K. Allen, T. P. Wangler, “Beam halo definitions based upon moments of the particle distribution”, Physical Review Special Topics – Accelerators and Beams, Vol. 5, 124202 (2002).

[11] E. Sargsyan, “End-to-end simulations of CERN LINAC4”, HIPPI Annual Meeting, Juelich, Germany, September 2006, http://www.fz-juelich.de/ikp/hippi/autumn2006/HIPPI06_Sargsyan.pdf