EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE

CERN - PS DIVISION

PS/ RF/ Note 97-18

PRELIMINARY DESIGN OF A 352 MHZ DRIFT TUBE LINAC WITH EXTERNAL FOCUSING

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Abstract

For a Superconducting Proton Linac (SPL) injecting into the CERN PS, as well as for most of high energy SC linac proposals, an optimum transition energy between low energy Room Temperature (RT) and high energy Super Conducting (SC) cavities lies somewhere between 100 and 200 MeV [1]. For the aims of the preliminary SPL feasibility study the transition energy does not need to be optimised, and it has been somehow arbitrarily fixed to 150 MeV. The optimum output energy of the RFQ injector being around 5 MeV, a specific RT structure is needed to cover the range between 5 and 150 MeV. RF standardisation with the SC section advises to operate also the RT part at a frequency of 352.2 MHz.

This study first compares the features of four different structures suitable for this energy range, and then concentrates on a design based on a Drift Tube Linac (DTL) made up of short (8 $\beta\lambda$ long) tanks without quadrupoles inside the drift tubes. In this design, doublets or triplets between the tanks can provide the focusing. The RF structure has been optimised, and then a complete linac layout between 5 and 150 MeV has been outlined. The multiparticle beam dynamics is studied by means of the code PARMILA and of a specially written interface program, to allow the analysis with PARMILA of strings of DTL tanks with external focusing.

Geneva, Switzerland
25 May 1998

1. Comparison of RF Structures

Four different RF structures have been considered. For each of them, some cells have been designed in the energy range 5-150 MeV for a frequency of 352.2 MHz, in order to compare their shunt impedance. The simulation codes used are either the 2D-code SUPERFISH [2] or the 3D-code MAFIA [3]. The structures analysed are:

a. The "standard" DTL (or "Alvarez" linac), with a quadrupole inside each drift tube, long tanks (about 10m), FODO focusing, post coupler stabilisation.
b. A DTL-like design, with short (8 cell) tanks without quadrupoles inside the drift tubes, and quadrupole doublets or triplets between the tanks providing the focusing.
c. An interdigital-H (IH) structure, similar to those currently used for heavy ions, but here used for protons in the range 5-75 MeV. The cells could be arranged in short tanks, with focusing provided by quadrupole doublets between the tanks.
d. A Coupled Cell Linac (CCL) structure made of slot-coupled cells operating in the π-mode. The cells can be arranged in 5-cell tanks similar to the LEP1 accelerating cavity. Here again focusing should be provided by quadrupoles between the tanks.

Figure 1 shows the calculated effective shunt impedance ZT^2 (MΩ/m, linac definition $ZT^2=(E_0T)^2/P$) as function of beam energy for the four structures. Each point on the plot corresponds to a simulation. For a fair comparison, the bore radius is the same (15 mm) for all the structures, and the computed shunt impedance is multiplied by a factor that takes roughly into account the additional losses at the tank end walls and at the coupling slots. The cross in the graph (32 MΩ/m at 30 MeV) corresponds to the shunt impedance of the CERN Linac2 (202 MHz).

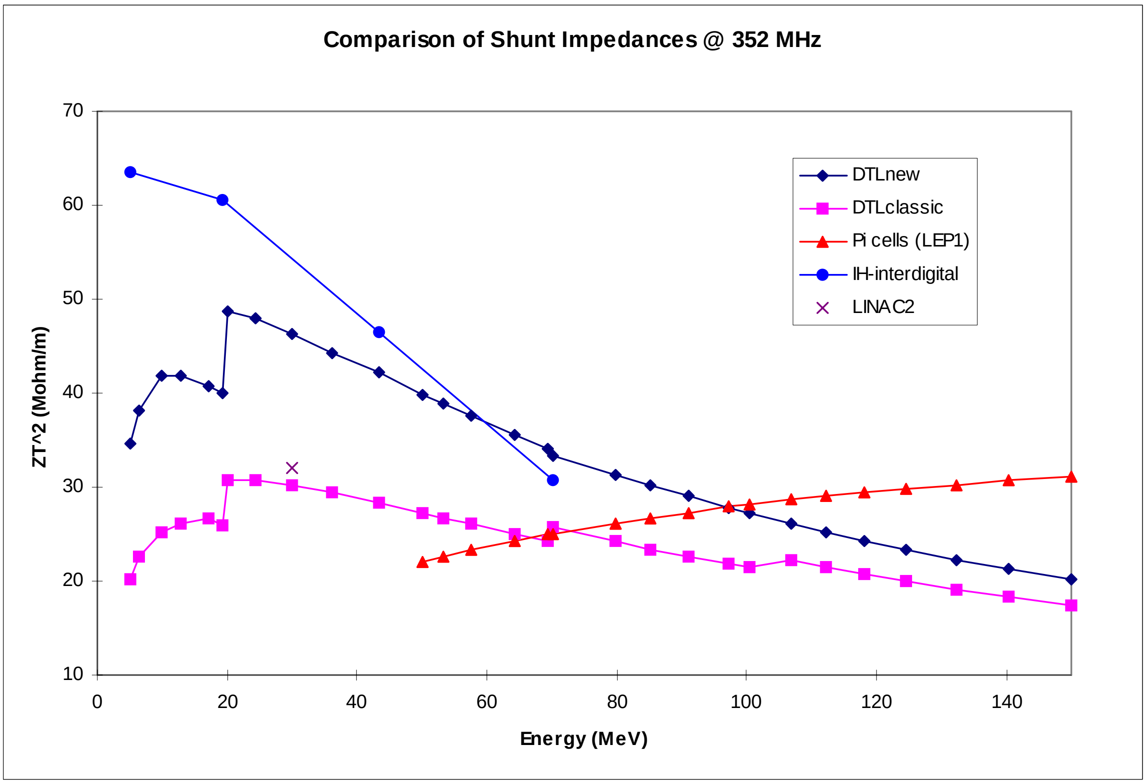

Figure 1: Comparison of shunt impedance at 352 MHz.

The standard DTL has the lowest shunt impedance. At 30 MeV, this is even lower than the Linac2 shunt impedance, in spite of the higher frequency (for a symmetric dimension scaling, shunt impedance scales as the square root of the frequency). The reason is that, in order to house standard quadrupoles, the drift tube diameter does not scale with frequency, making standard DTL structures at high frequency particularly inefficient. Some development could of course be done to find small (permanent?) quadrupoles to be used at high frequency. If instead the quadrupoles can be taken completely out of the drift tubes, the shunt impedance could be, depending on the frequency, between 120% and 40% higher than for a standard (curve "DTL new" in the Figure).

An interesting curve is the one of the IH structure, however less accurate than the others, being derived from a small (four) number of 3-D simulations done with a less precise mesh by the program MAFIA. Even at 352 MHz, an unusually high frequency for the IH, and for such high β's, this structure keeps its high shunt impedance up to about 80 MeV. Beyond, it rapidly falls down to unacceptable values. However, the construction of an IH for protons between 5 and 80 MeV would be extremely challenging from the point of view of mechanics and alignment. The cavity diameter would be only 15.5 cm at 5 MeV. At higher energy, the diameter becomes larger, 22.5 cm at 70 MeV, but the shunt impedance goes dramatically down. Nevertheless, these dimensions are probably not unrealistic, if we think that such a structure would follow a 352 MHz 4-vane RFQ with nearly the same diameter (and a similar cavity mode, TE210 instead of TE110) and made up of longer units than what required for a proton IH.

The fourth curve shows the typical behaviour of a CCL with cells $\beta\lambda/2$ long. At low energies the cells are short, and the stray capacitance between cell walls keeps the shunt impedance low. At high energy, the capacitance is concentrated on the gap and the higher acceleration per unit length of the π mode leads to shunt impedance higher than that of a DTL. A π-mode structure at 352 MHz is more efficient than a standard DTL from 80 MeV and more efficient than a DTL with external focusing from 100 MeV.

2. Choice of Structure

Shunt impedance is not the only figure of merit for the selection of a structure. While the shunt impedance decides the RF cost of a linac, the structure cost is another important parameter, related mainly to the easiness of construction and to the tolerances required in manufacture and alignment. From this point of view a standard DTL is again the most expensive, because the quadrupoles impose a very high precision in aligning the drift tubes. The other structures on the contrary allow separating the tuning and adjustment of the RF structure from the alignment of the quadrupoles. As far as cooling is concerned, again the standard DTL is the most difficult to cool, considering that 50% of the RF losses occur on the drift tube surface and have to be cooled from the thin stem, together with the losses on the quadrupole.

However, a standard DTL is mandatory for low energy and/or high current, i.e. where space charge and RF defocusing are stronger. The RF defocusing goes down with energy (like $1/\beta\gamma^2$), as well as do the space charge forces, meaning that at high energy less focusing is needed, and a solution with external focusing should be possible. In particular, the recent advances in RFQ technology have increased the input energy in a DTL. Moreover, the generalised use of low current H- beams makes a DTL design with external focusing more attractive. In particular, for the DTL of the SPL design and 10 mA current a solution with external focusing (triplets or doublets) should be possible already from 5 MeV. This case will be analysed in the following.

3. Cell and Tank Design

The program SUPERFISH has been used for the design of the linac cells, in its version DTLFISH, intended for the routine calculations required for the design of a DTL. In total, 29 basic cells have been computed, from 5 MeV up to 150 MeV. Figure 2 shows 4 typical cell shapes at different energies. The fact that the drift tube does not have to house a quadrupole gives some freedom in the design of the drift tube profile. A slope has been added to the tubes, in order to have a lower cell capacitance and therefore higher shunt impedance. For the same reason, the tube diameter is the minimum allowed by mechanical stability and cooling considerations.

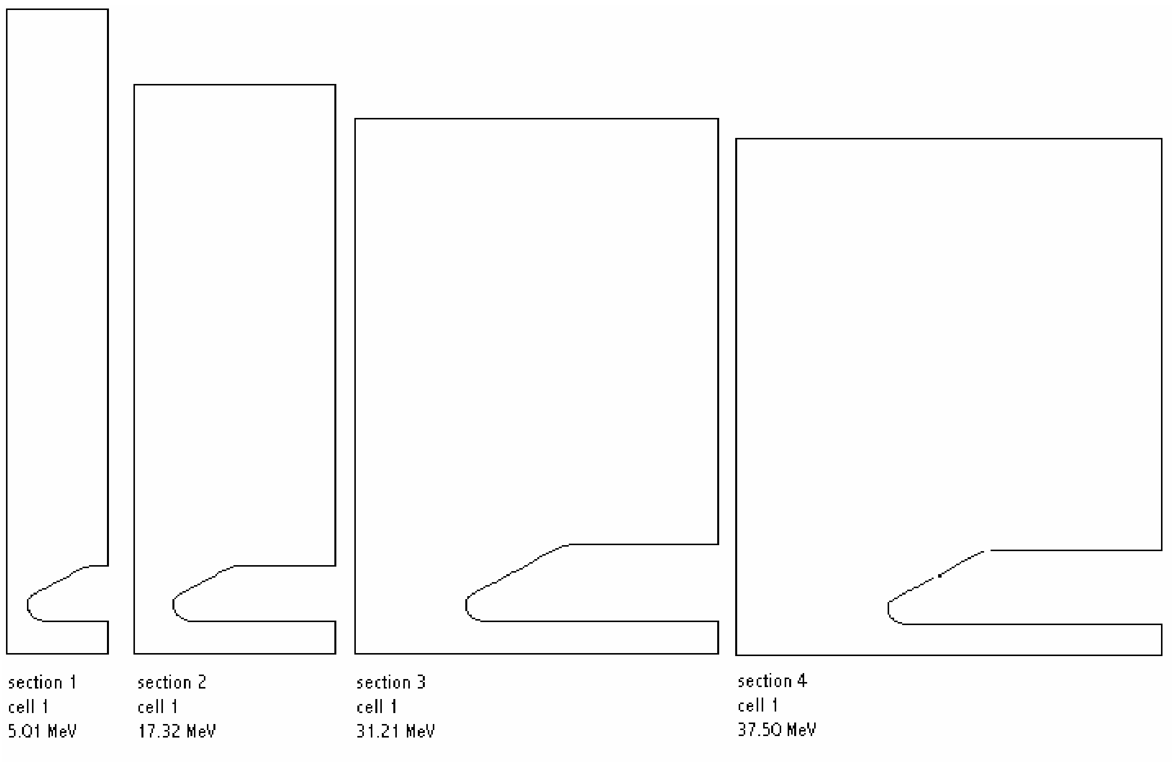

Figure 2: DTL cell shape at four different energies.

The linac has been divided into 4 sections, the cells shown in Figure 2 corresponding to the beginning of each section. Passing from one section to the next, the drift tube profile is slightly re-optimised, and the tank diameter reduced, in order to keep the resonant frequency. The bore radius is 1.5 cm in the first two sections, and then is increased to 1.8 cm. The cell parameters have been only preliminarily optimised for shunt impedance, further optimisation being in general possible. In particular, the bore radius should be redefined after the beam dynamics simulations and in relation with the beam duty cycle (tolerable level of halo particle loss). Table 1 gives a summary of the main structure parameters for the 29 computed cells. The peak field given in the Table corresponds to an accelerating field E0 = 2 MeV/m, and is everywhere below the Kilpatrick field (18.5 MV/m at 352 MHz). Figure 3 shows the computed shunt impedance (that includes the stems but does not take into account the end wall losses), and the corresponding gap over cell length parameter.

section	Energy W	beta	zt^2	g	L	Bore r	L/2	g/L	Ltube	Emax	Diameter
	[MeV]		[MOhm/m]	[cm]	[cm]	[cm]	[cm]		[cm]	[MV/m]	[cm]
1	5.014	0.103	49.520	1.777	8.760	1.500	4.380	0.203	6.983	14.03	59
1	6.550	0.118	54.370	2.259	10.000	1.500	5.000	0.226	7.741	13.4	59
1	10.039	0.145	59.710	3.304	12.346	1.500	6.173	0.268	9.042	12.75	59
1	12.969	0.165	59.910	4.126	14.000	1.500	7.000	0.295	9.874	12.42	59
1	17.047	0.188	58.265	5.212	16.000	1.500	8.000	0.326	10.788	12.28	59
1	19.313	0.200	57.090	5.789	17.000	1.500	8.500	0.341	11.211	12.23	59
2	20.080	0.204	69.560	3.349	17.324	1.500	8.662	0.193	13.975	18.03	52
2	24.313	0.223	68.455	4.057	19.000	1.500	9.500	0.214	14.943	17.18	52
2	30.123	0.247	66.055	5.018	21.054	1.500	10.527	0.238	16.036	16.77	52
2	36.290	0.270	63.277	6.015	23.000	1.500	11.500	0.262	16.985	16.47	52
2	43.338	0.294	60.220	7.122	25.000	1.500	12.500	0.285	17.878	16.23	52
2	50.206	0.315	56.984	8.159	26.769	1.500	13.385	0.305	18.610	16.1	52
2	53.225	0.323	55.637	8.605	27.500	1.500	13.750	0.313	18.895	16.07	52
2	57.536	0.335	53.639	9.227	28.500	1.500	14.250	0.324	19.273	16.04	52
2	64.405	0.353	50.662	10.190	30.000	1.500	15.000	0.340	19.810	16.02	52
2	69.265	0.364	48.662	10.850	31.000	1.500	15.500	0.350	20.150	16.02	52
3	70.295	0.367	47.721	9.491	31.206	1.800	15.603	0.304	21.715	17.04	49
3	79.695	0.388	44.745	10.635	33.000	1.800	16.500	0.322	22.365	16.95	49
3	85.286	0.400	43.080	11.294	34.000	1.800	17.000	0.332	22.706	16.93	49
3	91.142	0.411	41.405	11.970	35.000	1.800	17.500	0.342	23.030	16.81	49
3	97.271	0.423	39.730	12.652	36.000	1.800	18.000	0.351	23.348	16.82	49
3	100.431	0.429	38.903	13.000	36.498	1.800	18.249	0.356	23.498	17	49
4	106.886	0.441	37.221	12.768	37.500	1.800	18.750	0.340	24.732	17.66	47
4	112.355	0.450	35.983	13.327	38.300	1.800	19.150	0.348	24.973	17.66	47
4	118.030	0.459	34.754	13.896	39.100	1.800	19.550	0.355	25.204	17.58	47
4	124.668	0.470	33.380	14.540	40.000	1.800	20.000	0.364	25.460	17.76	47
4	132.376	0.482	31.872	15.278	41.000	1.800	20.500	0.373	25.722	17.8	47
4	140.451	0.493	30.385	16.023	42.000	1.800	21.000	0.382	25.977	17.86	47
4	149.999	0.507	28.744	16.876	43.125	1.800	21.563	0.391	26.249	17.93	47

Table 1: parameters of DTL cells

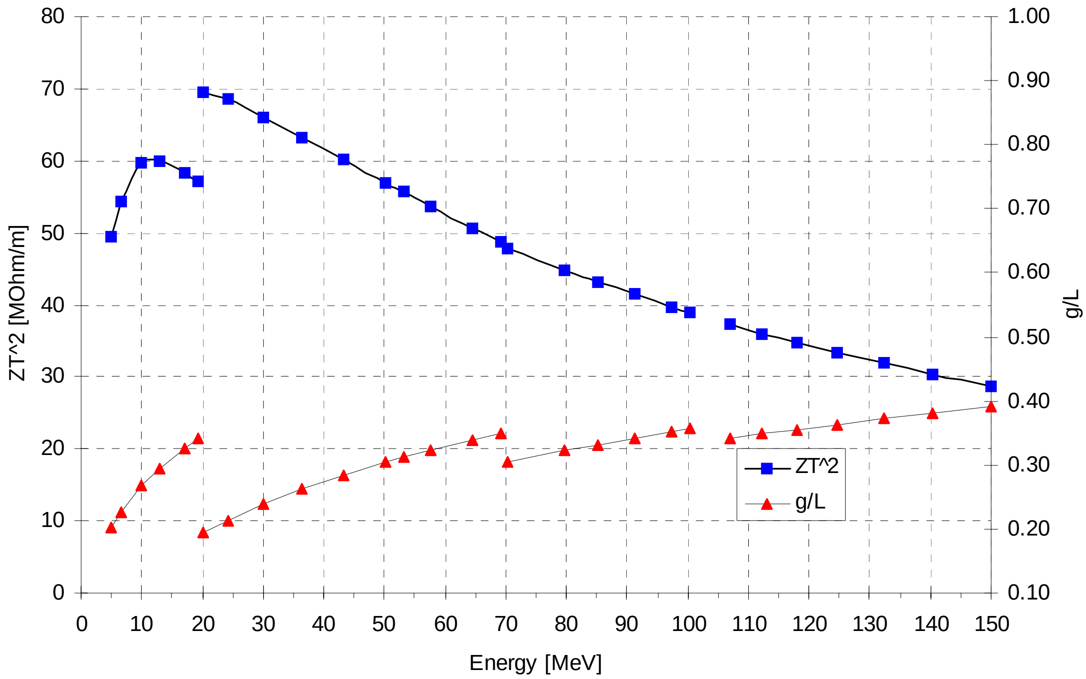

Figure 3: Shunt impedance and g/L as function of energy

The cells can be arranged in many ways inside tanks, the number of cells per tank being finally decided by the beam dynamics. A large number of cells per tank leads to a less expensive linac (less tanks and less end wall losses) but a longer focusing period leads to a larger beam size inside the tanks and the consequent risk of beam losses. In the following will be analysed a design with 8 cells per tank, corresponding to a length of 8 βλ (from 0.73 m at 5 MeV up to 2.9 m at 150 MeV), constant all along the linac. The number of cells per tank is kept constant to avoid changes in the focusing period and the related mismatch. The intertank spaces have to house the quadrupoles and some diagnostics (beam transformers and position pick-ups), and a reasonable distance between tanks has been taken as 3 βλ. This leaves little space for diagnostics after the first tanks, while after few tens of MeV the space is large enough to house many types of diagnostics devices. In total, the linac period would be 11 βλ (see Figure 4). Again, this periodicity has to be considered as a starting assumption, to be checked by beam dynamics calculations, while an optimum would be the outcome of more detailed calculations, adapted to the particular operating conditions.

In order to define the linac length, one still needs to choose the mean field and the synchronous phase. The mean field E_0 has been fixed here at 2 MV/m all along the linac. This is about the same as in the CERN Linac2 and gives low peak surface fields, everywhere below the Kilpatrick limit. This is particularly important for a linac running CW or at a high duty cycle, while for low duties the mean field could be risen, leading to a shorter linac, however requiring more RF power. This parameter could be also changed in a further round of optimisation. As starting assumption, a safe synchronous phase angle of -30 deg has been taken for all the linac.

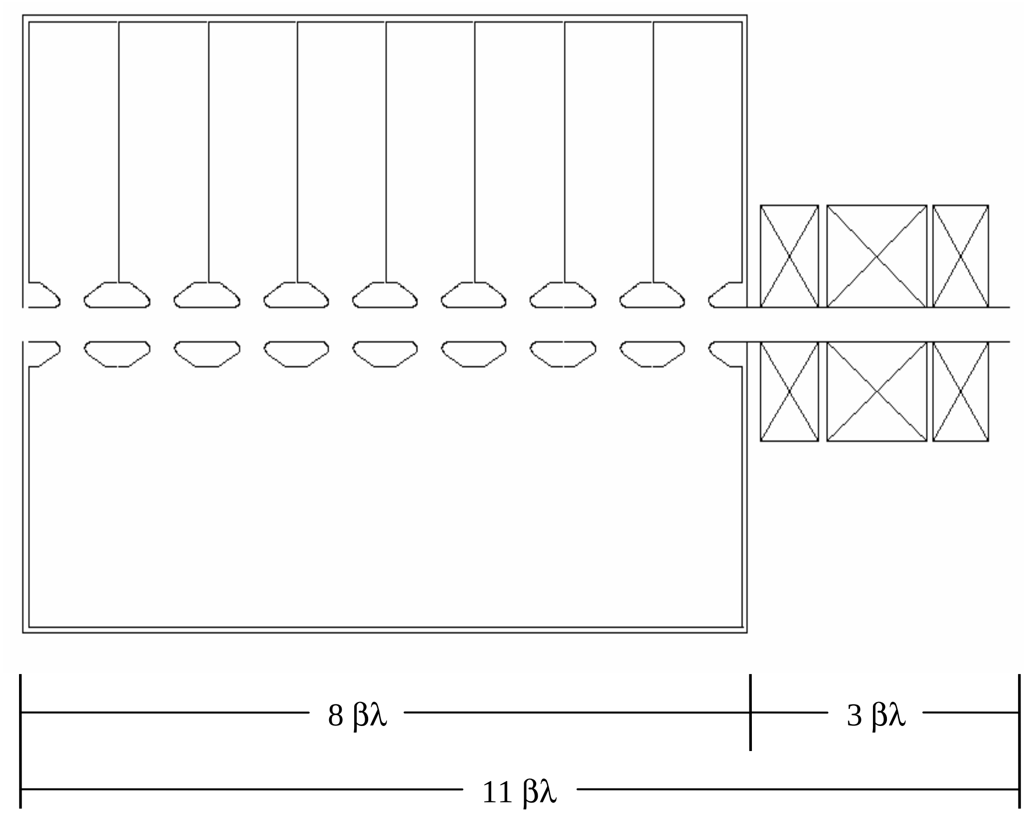

Figure 4: basic period of a DTL with external quads (here a triplet).

With these parameters, one can outline the overall linac layout between 5 and 150 MeV, in terms of number of tanks, length and RF power needed. Table 2 shows the main parameters for a linac divided into 5 sections and a mean beam current of 10 mA. Here the section 2 of Table 1 has been divided in two sections, from 20 to 50 MeV and from 50 to 70 MeV, to make possible a comparison with Linac2 (50 MeV). The overall power needed by the linac is slightly below 9 MW, meaning that 9 or 10 klystrons of the LEP type (1 MW maximum output power) would be needed for the DTL. The power distribution system, from the klystrons to the DTL tanks, could be a branch system of the LEP type, with one klystron feeding 8 or more tanks in the first modules and only 2 tanks in the last section. A more innovative solution based on bridge couplers connecting all the tanks in a module could be probably applied, at least for the first modules where the intertank distances are smaller, but would need some development.

Sec.	Win	Wout	ΔW	cells	tanks	Structure Length	Acc. Gradient	Total Length	Structure Power	Wall Power	Beam Power	Total Power
	[MeV]	[MeV]	[MeV]			[m]	[MeV/m]	[m]	[MW]	[MW]	[MW]	[MW]
1	5.00	20.02	15.02	92	12	11.91	1.26	16.37	0.53	0.06	0.15	0.74
2	20.02	50.32	30.30	96	12	21.30	1.42	26.63	1.13	0.07	0.30	1.50
3	50.32	70.33	20.01	50	6	14.51	1.38	18.14	0.88	0.03	0.20	1.11
4	70.33	100.16	29.83	64	8	21.74	1.37	24.46	1.53	0.05	0.30	1.88
5	100.16	150.25	50.10	101	13	40.36	1.24	45.41	3.11	0.09	0.50	3.70
				403	50	109.83		131.01	7.18	0.30	1.45	8.93

Table 2: RF structure parameters for the DTL with external quadrupoles.

4. Beam Dynamics Analysis Tools

The most commonly used and reliable beam dynamics code for linac applications, PARMILA [3], does not allow calculating in a single run multitank DTL structures with more than one quadrupole between tanks. However, transfer lines can be included in the computations before or after a DTL tank and macroparticle coordinates can be transferred from one run to another. Therefore, one has to prepare separate PARMILA input files for each period made of a tank and the following focusing section, and then run PARMILA for each of them, taking every time as input the particle distribution obtained from the previous run.

To make this process automatic and simulations faster, an interface program to run PARMILA for a multitank DTL from a Windows environment has been written in Visual Basic. The program called PARMINT (=PARMila INTerface) is available on the NICE network (G:\HOME\V\VRETENAR\RFLin\Parmint.exe for the case with triplet focusing, and G:\HOME\V\VRETENAR\RFLin\Parmintd.exe for the doublet focusing). A typical PARMINT window after a run (51 periods) is shown in Figure 5.

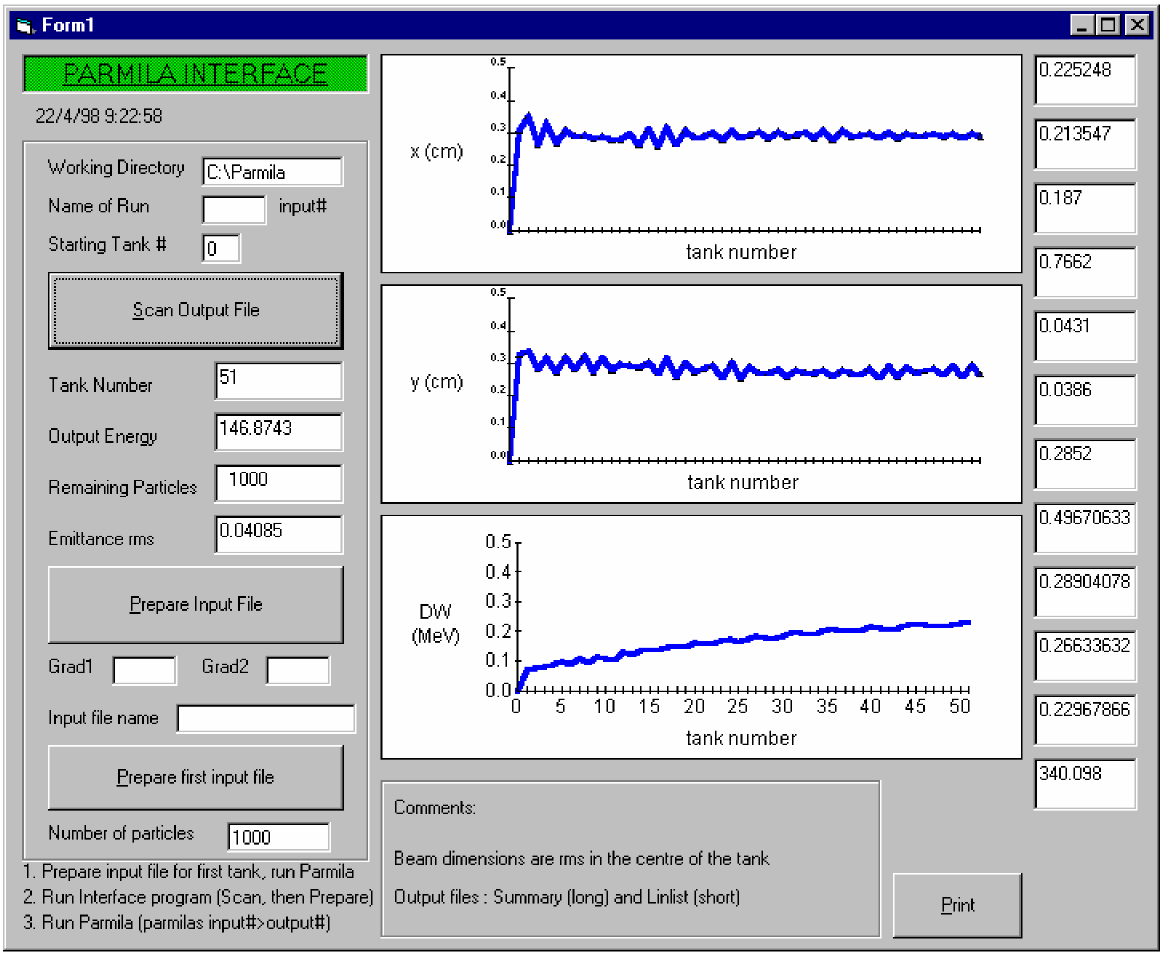

Figure 5: PARMINT (=PARMila INTerface) control window at the end of a run with 51 tanks (from 5 MeV to 150 MeV).

To run the program, one has to prepare a first input file for PARMILA containing the input beam characteristic, and run it for the first tank. Then, the buttons in the PARMINT window allow to scan the output file, extracting some parameters that are visualised on the screen, numerically and graphically, for a rapid check of the dynamics, and to prepare the input files for the next period. The beam dimensions in the three planes (x, y and energy) at the centre of each tank are visualised in three plots.

This approach, considering the intertank quadrupoles as transfer lines, has the consequence that the phase advances and the corresponding quadrupole gradients have to be calculated externally to the program. This has been done using TRACE3D [4], a linear program that calculates beam envelopes in a transport line. TRACE is particularly useful in the calculation of matching parameters, and it has been used for calculating matched quadrupole gradients for some periods along the DTL. A numerical interpolation of the TRACE calculated gradients was then given to PARMINT and used in the PARMILA simulations. Figure 6 shows a TRACE3D simulation of the first 5 periods (from 5 to 10 MeV) of a DTL with external quadrupoles, triplets in this case, after matching with TRACE. Input emittances are shown at the left side of the picture (top = transverse, bottom = longitudinal), while output emittances are at the right side.

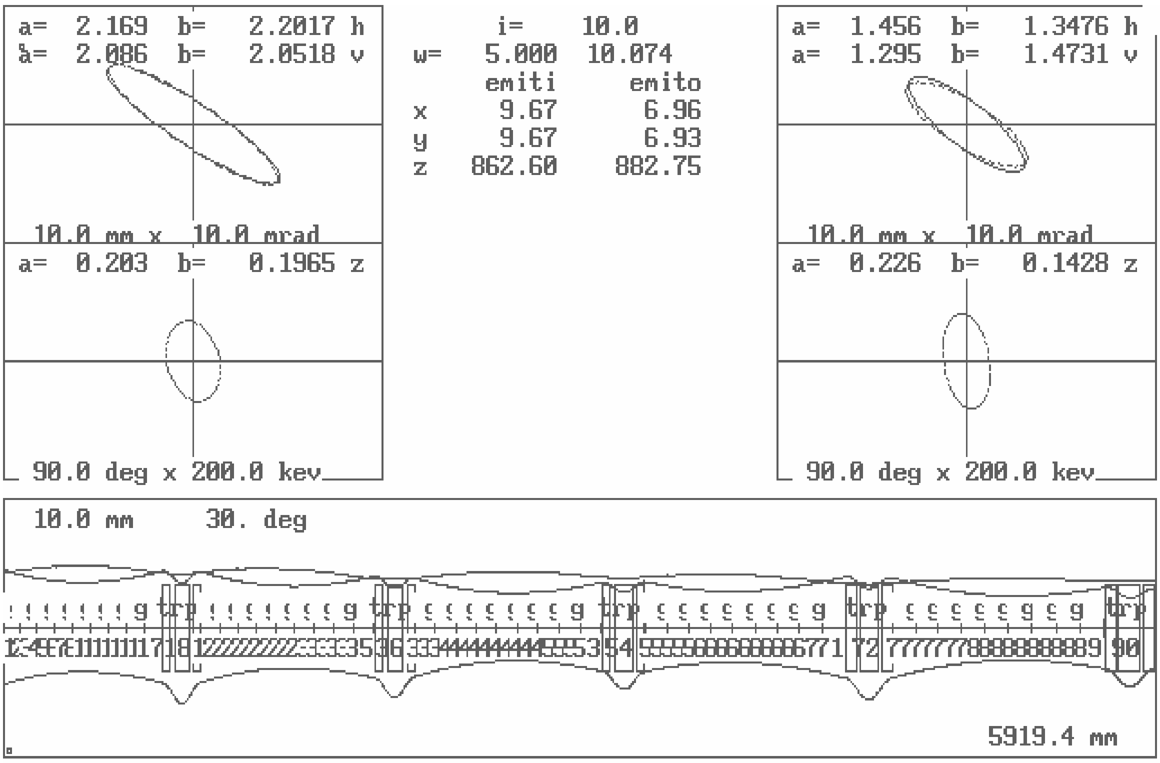

Figure 6: Simulation with TRACE3D of the first 5 periods of a DTL with external quadrupoles (triplet case).

A scheme in the form of a flow chart of the approach used for designing the DTL with external quadrupoles is shown in Figure 7.

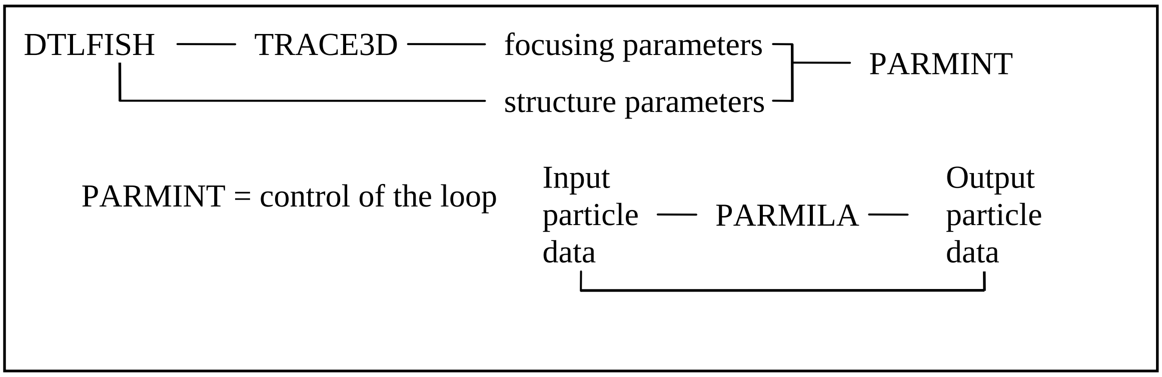

Figure 7: Computational approach used in the design of the DTL with external quadrupoles.

5. Beam Dynamics Calculations

Two different cases have been analysed, triplet and doublet focusing between tanks. Triplets have the advantage of giving a round beam inside the tanks, as can be seen in Figure 6, offering the best filling of the cavity aperture. They are particularly suited where particle losses are a concern, as in CW linacs. In comparison, doublet focusing requires less magnetic elements, leaves more space for diagnostics (the distance between tanks has been kept to 3 $\beta\lambda$ in both cases), but produces a slightly larger mean beam size in the tanks. Some cases were studied, with input emittances of 0.21 and 0.3 π mm mrad (rms, normalised) for the transverse planes and 0.2 and 0.3 deg MeV (rms, at 352 MHz) for the longitudinal plane.

In the first simulations, 10000 macroparticles were generated and transported along the linac, while for the last runs only 1000 particles were taken, giving reliable enough results with much faster computation times. In all the cases shown here the transmission was 100%.

For the case with triplets, transverse input emittance 0.21, current 10 mA and a constant phase advance per period of 88deg the transverse emittance growth between 5 and 150 MeV is only 5%. Transverse tune depression due to space charge went from 0.82 at 5 MeV to 0.95 at 150 MeV. The ratio between bore and rms beam radius goes between 5 at low energy and 10 at high energy. This value is considered as large enough to minimise high-energy losses of halo particles. A complete set of plots from this simulation is given in Figures 7 to 10.

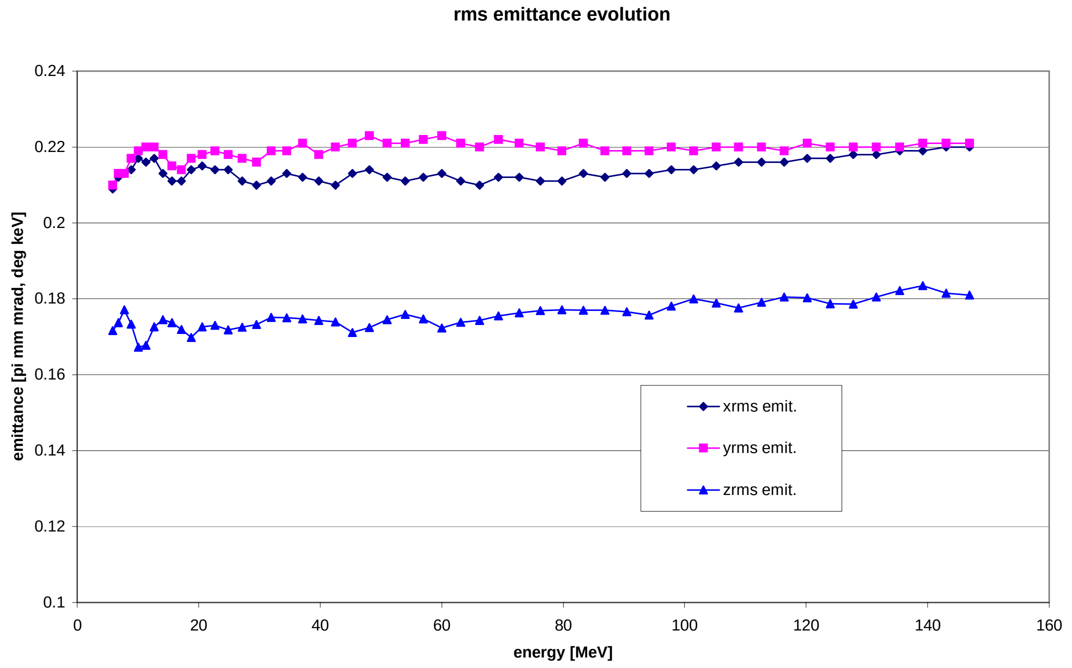

Figure 7: rms emittances evolution along the DTL, case of triplets, 10 mA

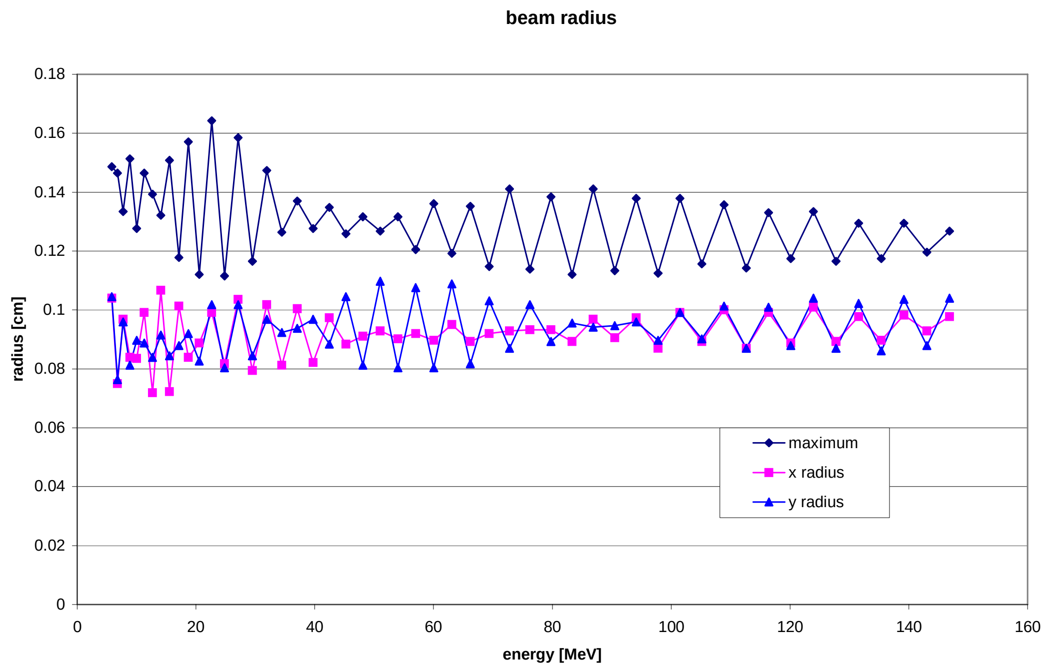

Figure 8: rms beam radius at tank centre along the DTL. Case of triplets, 10 mA

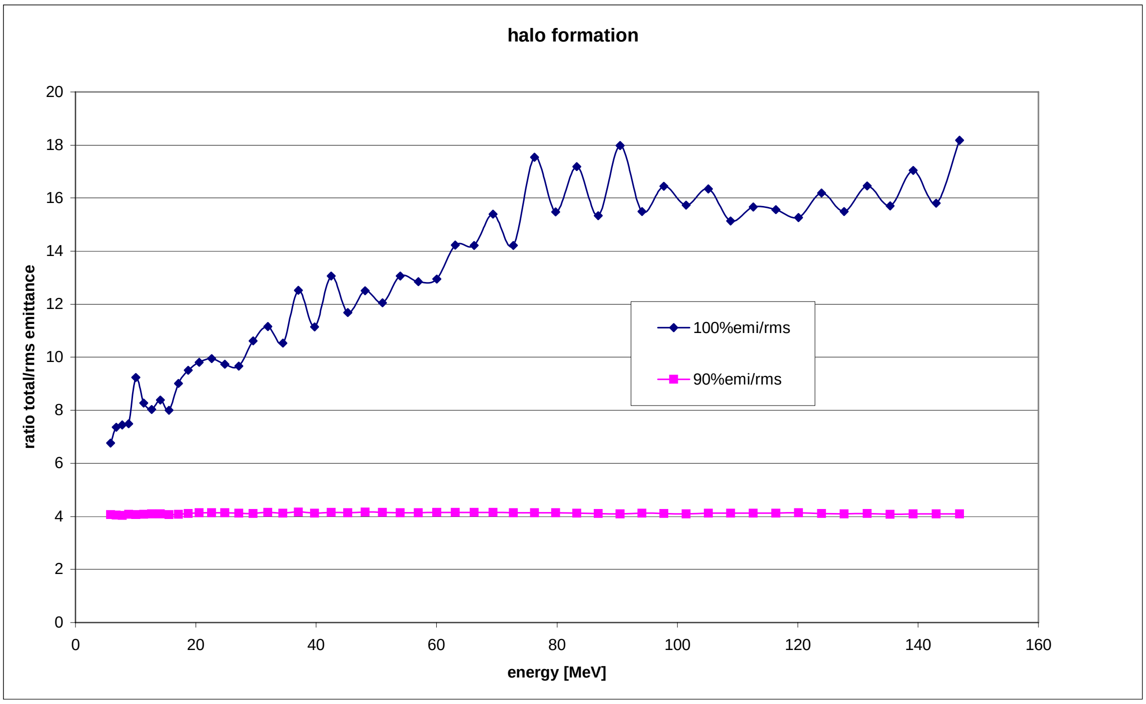

Figure 9: ratio total/rms emittance along the DTL for 100% and 90% emittance. Case of triplets, 10 mA.

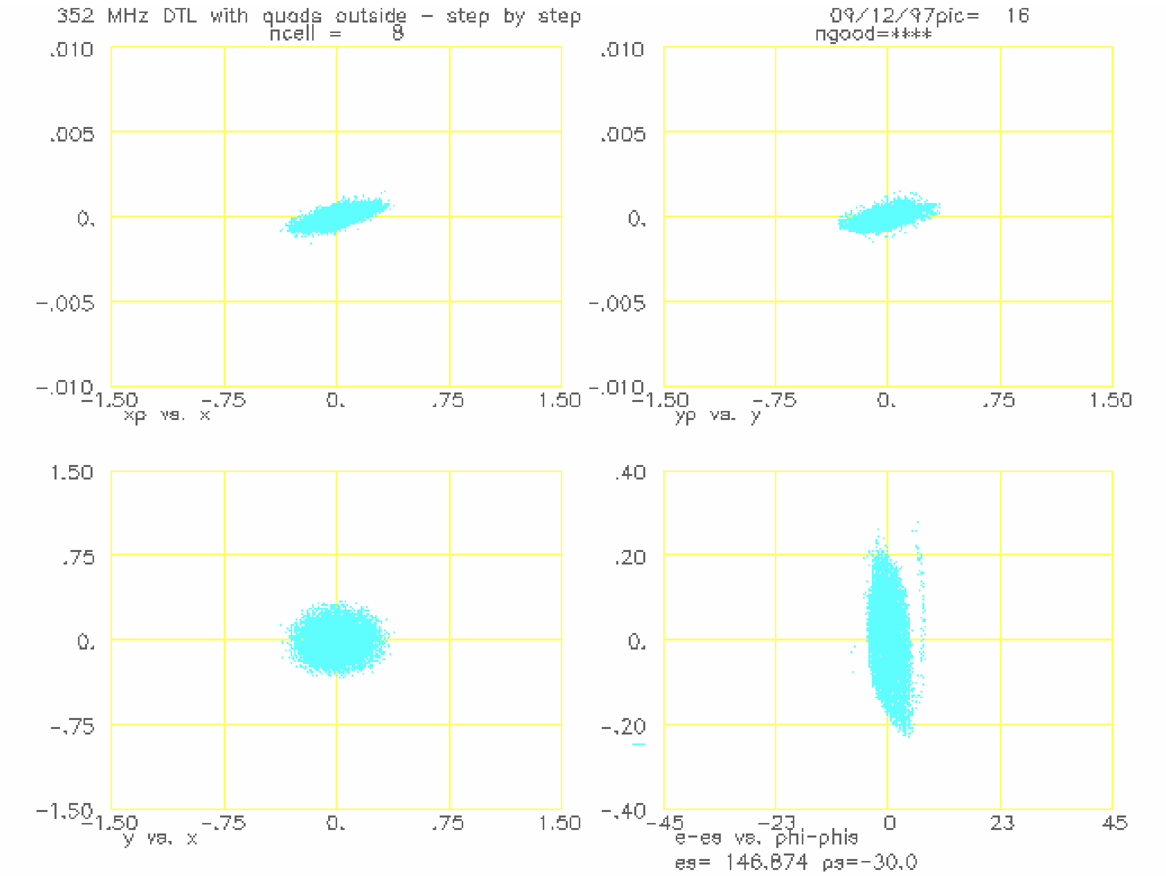

Figure 10: PARMILA output (emittances and beam dimensions) at the centre of the last tank (146.8 MeV). Case with triplets, 10 mA, 10000 macroparticles

More simulations have been carried out with doublet focusing. Two sets of input emittances were tried, 0.2 transverse and longitudinal and 0.3, again transverse and longitudinal. As well, two different beam currents were tried, 10 mA and 30 mA. In all the cases, the transmission remains 100%. For both the input emittance sets, emittance growth remains small (of the order of 5%). Instead, increasing the current to 30 mA without changing the quadrupoles led to a large mismatch and a consequent large emittance growth (40%), that can be probably corrected by re-matching for the increased space charge the low energy part of the linac. However, the current limit for such a structure at low energy (5 MeV) should not be far from this value. The plots from the simulations with doublet focusing are given in Figures 11-17.

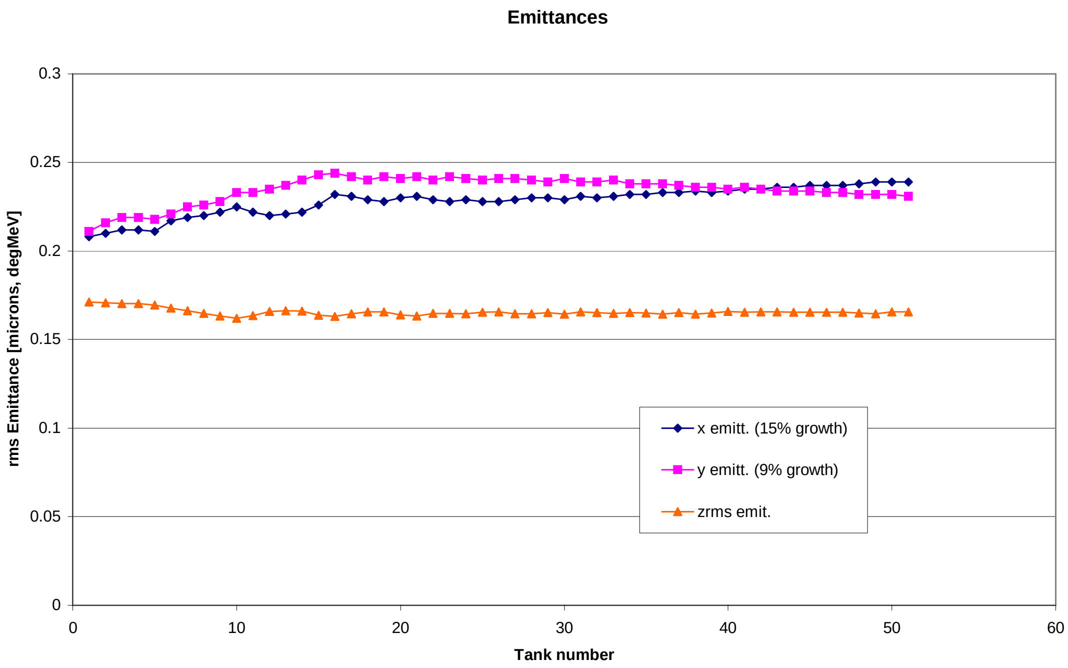

Figure 11: rms emittances along the DTL (doublets, 10 mA)

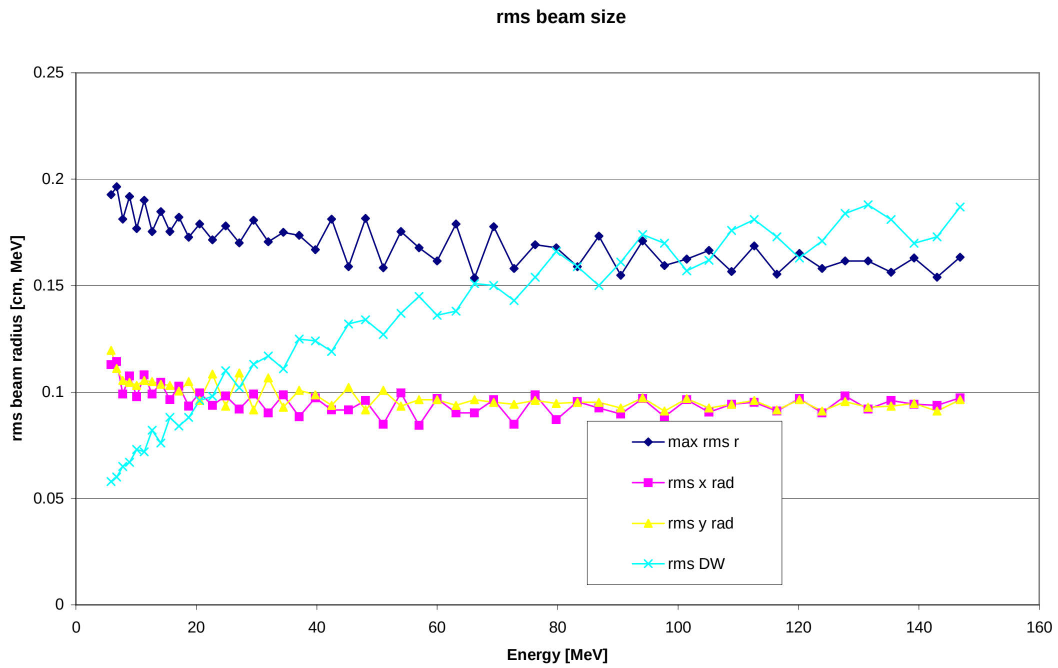

Figure 12: rms beam size along the DTL (doublets, 10 mA)

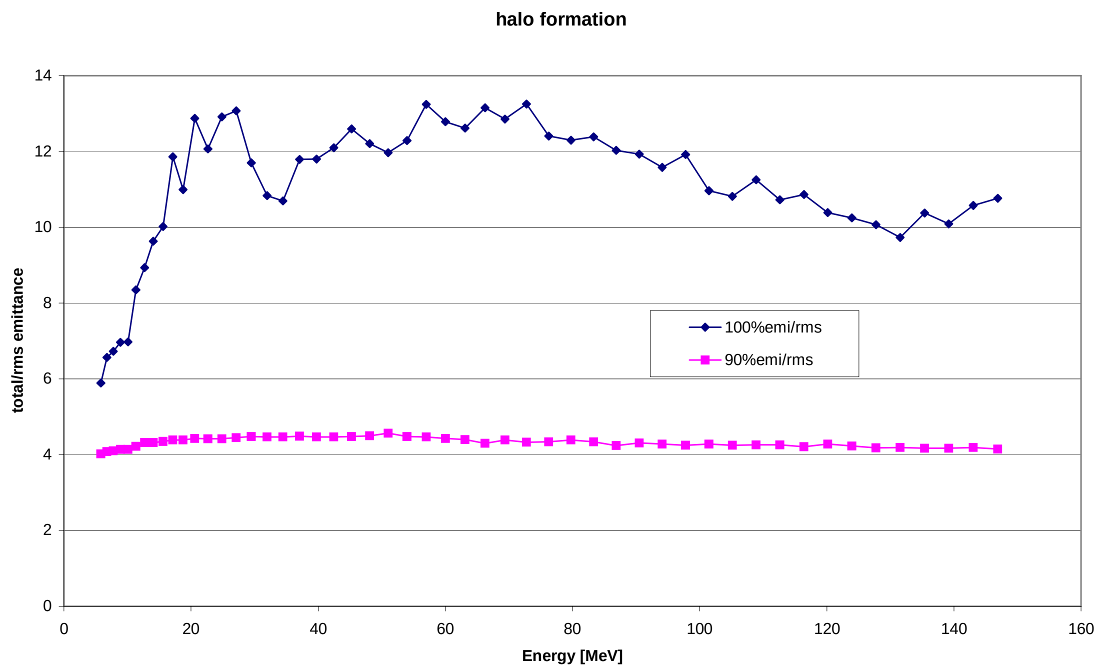

Figure 13: Total/rms emittances along the DTL (doublets, 10mA).

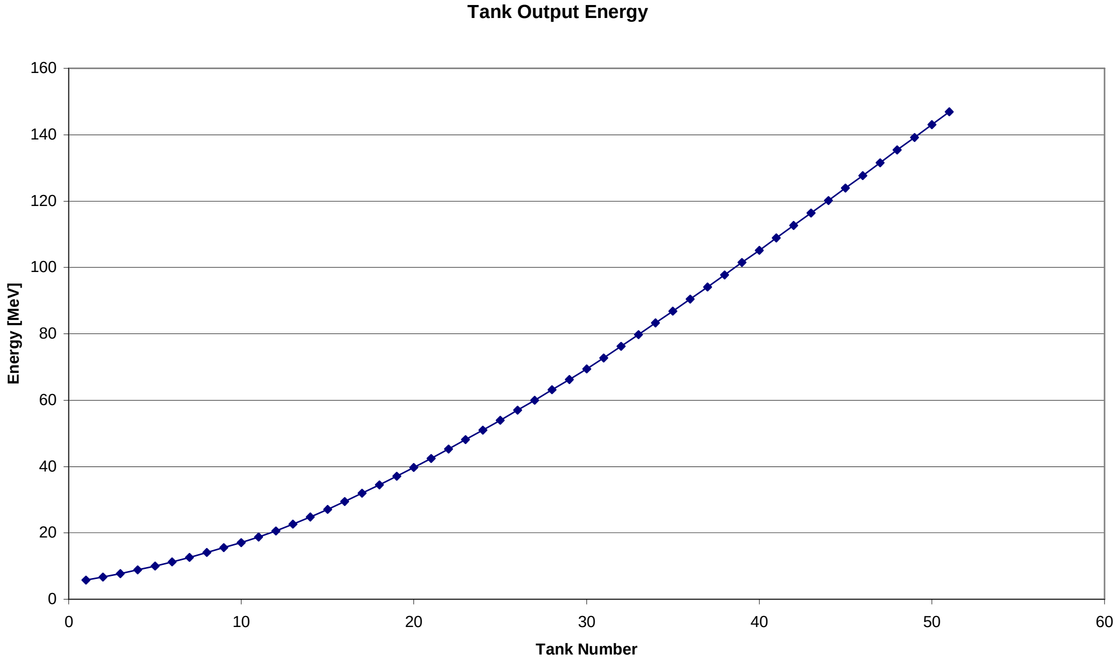

Figure 14: Energy as function of tank number

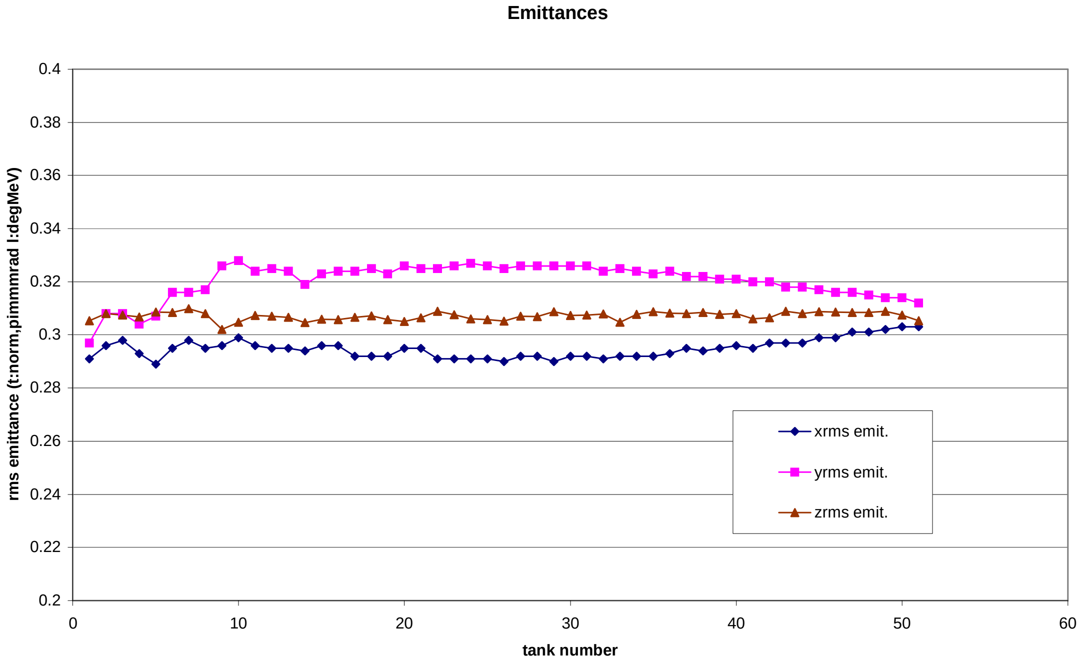

Figure 15: rms emittances along the DTL for 0.3 π mm mrad input emittance.

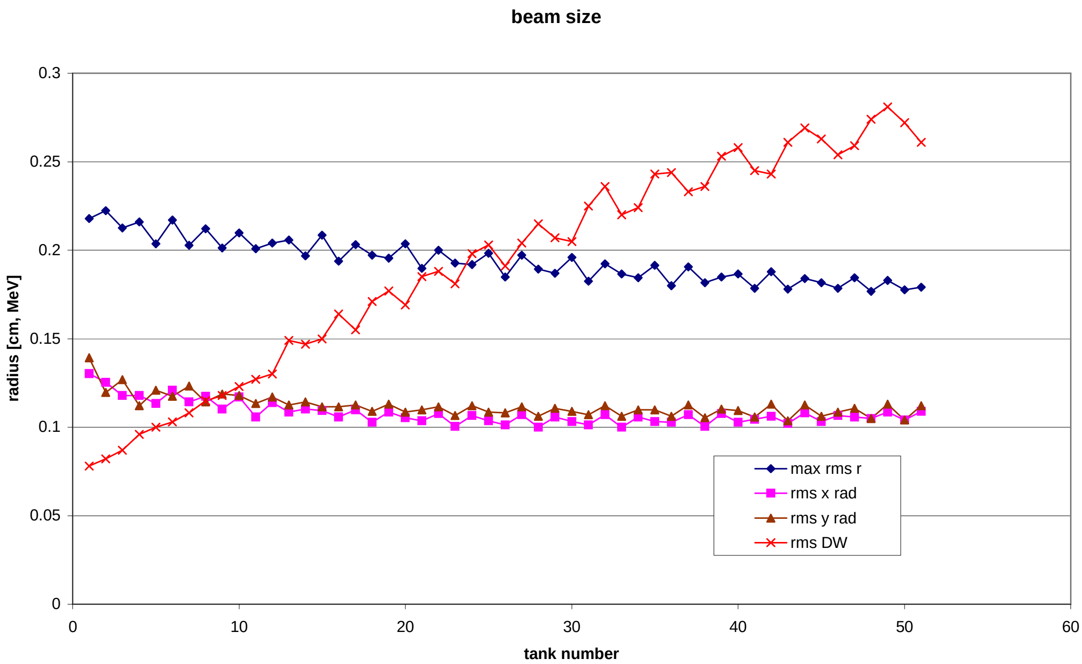

Figure 16: rms beam size along the DTL for 0.3 p mm mrad input emittance

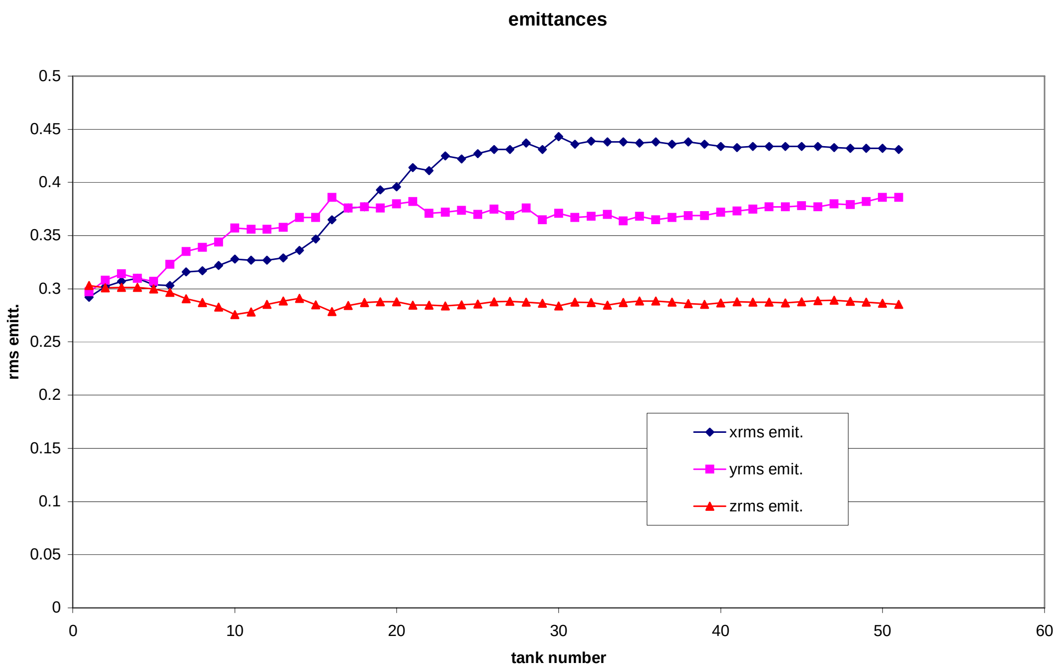

Figure 17: rms emittance evolution along the DTL (doublets, 30 mA, matching not optimised).

6. Conclusions and List of Parameters

For the DTL part of the SPL, a design with quadrupoles outside the tanks is feasible. In particular, the layout based on 8 cell tanks tried here gives a 100% transmission, a low emittance growth and a small enough ratio between beam size and aperture for a set of input emittances. For the low duty cycle of the SPL, a doublet focusing is preferable. Table 3 summarises some parameters of this DTL design.

Further studies should include a re-optimisation of the cell design and of the tank layout, the analysis of the bridge coupler option, a more detailed beam dynamics analysis and a precise calculation of the current limit for this design.

Parameter	Symbol	Value	Unit	Comments
Input Energy	Win	5	MeV	
Output Energy	Wout	150	MeV	
Peak Current	I	10	mA	up to 30 mA possible
Frequency	f	352.2	MHz	
Mean Field	E_0	2	MV/m	w/o TTF
Number of cells per tank	n	8		quads between tanks
Bore diameter	d_b	30 – 36	mm	
Synchronous phase	ϕ_s	-30	deg	
Transit Time Factor	T	0.65/0.85/0.70		at β=0.1,0.2,0.5
Shunt Impedance	ZT^2	37.5/52.5/25.0	MΩ/m	at β=0.1,0.2,0.5
Peak Surface Field	E_p	12 – 17	MV/m	0.6 - 0.9 Kilpatrick
Cavity Length	l	0.72 – 3.4	m	
Number of Cavities	N	51		
Overall Linac Length	L	152	m	
Peak Linac Power	P_{tot}	8.5	MW	beam+structure+margin
Number of Klystrons	N_k	9		LEP-type klystrons
Peak Klystron Power	P_k	0.72 – 1.1	MW	
Number of tanks per kl.		12 – 4		
Cavity Q-value	Q	~ 50000		
Focusing Period		11 $\beta\lambda$		8 $\beta\lambda$ tank, 3 $\beta\lambda$ intertank
Quadrupole Gradient	G	32 – 30 43 – 32	T/m	Doublets Triplets
Transv. Emittance	$\varepsilon_{x,y}$	0.3	π mm mrad	rms norm.
Long. Emittance	ε_l	0.3	deg MeV	rms, 352 MHz
Transv. Emitt. Growth	$\Delta\varepsilon/\varepsilon$	~ 5	%	
Beam Radius at tank centre	rb	0.3 – 0.2 ~ 0.25	cm	Doublets Triplets

Table 3: Main design parameters of the DTL with external quadrupoles.

7. References

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