The DTL approach for a 100 MeV CW linac.

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INTRODUCTION

The international community is showing growing interest in high intensity linacs for scientific, industrial, military and social applications. Proton linacs with final energies of about 1 GeV and CW operation are proposed for secondary beams production, tritium production, nuclear waste transmutation or energy production in sub-critical accelerator driven reactors. The beam intensities vary for different proposed applications; in particular for the Energy Amplifier proposed by professor Rubbia [1] the required power, between 10 and 30 MW, is given by a 10-30 mA proton beam at 1 GeV.

The beam current of 10-30 mA is relatively low for the linear accelerator structures and room temperature machines are therefore not very efficient. Consequently a superconducting linac has been proposed for the main part of the linac (0.1-1 GeV) [2,3], and a frequency of 352.2 MHz (LEP 2 frequency) has been chosen.

In this note we shall consider the possibility of using a room temperature Linac up to 100 MeV, with the conventional configuration of a proton source feeding a RFQ (Radio Frequency Quadrupole) followed by a DTL (Drift Tube Linac). The layout of the injector is shown in figure 1. The idea behind this choice is the following: the main linac is made superconducting because it has the biggest impact on capital costs and running costs, and the technology of this linac can be extrapolated from present experience. For the injector instead, that has smaller economical impact, it is worth to consider the most conservative option and to look where the problems are.

LINAC MAIN PARAMETERS

The beam design specifications of the proposed linac are summarised in Tab. I.

Table I : Beam Specifications.

Kind of particle	p	
Output energy	100	MeV
Duty Cycle	100	%
Beam current	30	mA
RMS normalised beam emittance	0.2	π mm mrad

The sequence RFQ-DTL is, by far, the most used scheme for proton linacs in the energy range of 10÷100 MeV. In our design both DTL and RFQ operates at the main linac frequency of 352 MHz; in this way we avoid any frequency jump, and the bore hole inside the DTL structure can be kept large enough to have a good margin between beam dimensions and machine acceptance . A similar scheme has been proposed for the low energy part of the French room temperature linac for tritium production (TRISPAL Project)[4].

The RFQ structure is, nowadays, the natural choice for the low energy part of any linear accelerator. It is very efficient up to the energies of few MeV giving a transmission in excess of 90% of the continuos beam coming from a source at energies of few tens of keV. The transition energy between the RFQ and the following structure is chosen depending on the particular application.

The DTL (called also Alvarez linac) is the downstream structure and shows a good efficiency up to few hundreds of MeV. From the rf point of view the structure operates in TM_{010} mode, loaded mainly by the capacitance between drift tubes. One important figure of merit is the shunt impedance (ZT^2)* which is inversely proportional to overall cavity capacitance. An efficient DTL asks therefore for small drift tubes. Unfortunately the drift tubes have to house the quadrupoles for transverse focusing. In order to reduce their dimensions permanent rare earth magnets or pulsed magnets (in pulsed linacs) are used. For a CW machine neither of those solutions is possible and electromagnetic, water cooled, magnets are necessary.

For this reason a CW DTL has a rather small shunt impedance, and the energy of the transition between RFQ and DTL in our case had to be chosen at 5

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* We quote the effective shunt impedance per unit length, defined as:

$$ZT^2 = \frac{\left(\frac{dW}{dz}\right)^2}{\frac{dP_d}{dz}\,(\cos\phi_s)^2}$$

where P_d is the dissipated power, W and ϕ_s are the synchronous particle energy and phase.

MeV. Moreover the efficiency of this linac is low because of the low peak current as already mentioned.

In Tab. II the main linac characteristics are summarised. For both RFQ and DTL we have simulated the fields in the rf structures and in the magnets, and the beam dynamics with multiparticle simulations. We used mainly LANL codes [5], that give a complete chain for the structure generation, rf and beam dynamics simulations. These codes are very well proved by the experience in many laboratories and by our personal experience, for what RFQ's are concerned.

Even if the simulations done up to now give a consistent set of linac parameters, this is not yet a linac design, since some engineering hypothesis are necessarily arbitrary in this stage, the exploration of parameter space have been very limited and certainly there is room for further improvements.

Table II Main parameters of the Linac (30 mA beam current).

		RFQ	DTL
Input Energy	MeV	0.075	5
Output Energy	MeV	5	100
RF Frequency	MHz	352.2	352.2
Total Length	m	6.0	80
Transmission	%	95.8	100.0
Output RMS Emittance			
ε_x	π mm mrad	0.22	0.23
ε_y	π mm mrad	0.20	0.24
ε_L	MeVdeg	0.17	0.20
RF power dissipation*	MW	0.7	8.3
Beam loading	MW	0.15	2.8
Quadrupoles diss.	MW	-	.6

THE RFQ

A peak current of 30 mA is rather small for a proton RFQ; the RFQ of CERN LINAC 2 for example transmits in excess of 250 mA. The optimisation design techniques available for the RFQ's are indeed depending on the beam current intensity because of the space charge forces and we are in the grey region between high and low space charge. In the first case the bunch compression, necessary to form the rf structure of the beam, is performed very slowly, so to keep a constant length of the bunch, being the phase extension of the bunch inversely proportional to the particle velocity. When the space charge is negligible instead the bunching is performed much more rapidly at low energy, and the RFQ is shorter. This second technique was developed and used for the construction of the CERN Lead Ion RFQ [6].

* SUPERFISH value multiplied by 1.3

For this design study we have generated the 5 MeV RFQ with both techniques, keeping the same intervane voltage and therefore the same power dissipation per meter. The list of the main parameters for the two structures is shown in table III. Figure 2 shows the energy gain in the structure and the transmission as a function of beam current in both cases.

Table III RFQ parameters.

		High space charge	Low space charge	design
Input Energy	*Wi*	0.075	0.050	MeV
Diameter of the cavity	*D*	200	200	mm
Shunt impedance	*Rs*	78	78	kΩ-m
Power diss. tank wall		31	31	kW/m
Power diss. electrodes		53	53	kW/m
Average radius	R_0	3.2	3.3	mm
Minimum aperture	*a*	1.8	1.9	mm
Synchronous phase	ϕ_S	-90÷-20	-90÷-20	deg
Modulation coefficient	*m*	1÷2.13	1÷2.43	
Adjacent vanes voltage	*V*	81	81	kV
Maximum surface field	E_s	36	34	MV/m (1.9 E_{KP})
Output RMS Emittance	ε_x	0.21	0.2	π mm mrad
(at current limit)	ε_y	0.22	0.2	π mm mrad
	ε_L	0.69	0.06	MeVdeg
Current limit (90% transmission)	I_{max}	75	10	mA
Length		6.0	4.4	m
RF power dissipation	P_d	0.51	0.37	MW

The result of the comparison is that to be able to accelerate 30 mA the high space charge design technique is needed and it requires 160 cm longer structure and 140 kW more power with respect of the 10 mA case generated with the heavy ions technique. Our high space charge design gives good transmission up to 75 mA, leaving some margin for pulsed operation. It has to be noted that for higher currents it is necessary to increase the extraction voltage from 50 to 75 kV, so to make the extraction with a small emittance possible. This contributes to make the RFQ longer.

In fig. 4 the beam envelopes for 30 mA case are shown. On the other hand is very possible that, with further studies, an intermediate approach for the intermediate space charge regime can be found.

The resonator type for a RFQ operating at 352 MHz is a four vanes structure. The cavity length is very long with respect of the rf wavelength in the free space and consequently particular care has to be put in the stabilisation of the field distribution with a suitable field stabilisation system.

The most challenging aspect of the RFQ construction design is the mechanical engineering of the structure. The machine has to operate in CW mode and has to be able to dissipate more than 80 kW/m, generated mainly on vane surfaces. In addition to this the mechanical tolerances of the structure are very tight, in the range of hundredth of mm, both for rf and beam dynamics reasons and they have to be kept during the operation in spite of the thermal stresses. At the present there are quite a few proposal of CW machines of this kind, but none of them has been demonstrated till now.

THE DTL

The acceleration efficiency of the RFQ falls down very rapidly in the range of 1 to 10 MeV and it is mandatory to change structure. As usual we consider a DTL as following accelerating segment and the transition has been put at 5 MeV trading off the RFQ low efficiency at the end of the structure with the higher DTL shunt impedance at its beginning.

The DTL section has been divided in three segments with intermediate energies of 20 and 70 MeV, as shown in table IV.

*Table IV :*DTL parameters.

Up to energy		20	70	100	MeV
Average electric field	E	0.9÷2	2	2	MV/m
Synchronous phase	ϕ_s	-30	-30	-30	deg
Tank diameter	D	540	480	420	mm
Drift tubes diameter	d	160	160	150	mm
Outer curvature radius		10	10	10	mm
Inner curvature radius		2.5	2.5	2.5	mm
Aperture diameter	$2R$	24	30	36	mm
Shunt Impedance	ZT^2	24÷29	22	19	MΩ/m
Quadrupole gradient		43	33	15	T/m
Quadrupole eff. length		44	62	155	mm
Quadrupole aperture		30	36	42	mm
Power diss. per quad.		1.4	1.7	1.7	kW
Number of quadrupoles		108	168	69	

In each segment the quadrupole magnets are identical and the geometrical parameters of the rf cavity, such as the tank diameter and the bore hole radius for the beam, are kept constant.

The focusing structure is a FODO with a transverse phase advance per period ($2\beta\lambda$) of about 25^0, guaranteed by a quadrupole strength of about 2 T. Since the drift tube length increases with β, the three families of quadrupoles have increasing length and decreasing gradient. Moreover, since at high energies the quadrupole design is less critical, the bore radius can be increased leaving more margin for the beam.

From the constructive point of view the DTL proposed is a standard structure suitable to stand the CW operation. The quadrupoles magnets, housed in the drift tubes, are made in soft iron with high saturation field, with hollow conductors for water cooling (4 by 3 mm with a 2 mm hole). The drift tubes are realised in bulk copper with an adequate cooling circuit. The dimensions of the tubes are dictated by the quadrupole magnets and by the thickness of the copper wall that has to be large enough to efficiently transmit the heat generated by the rf dissipation to the cooling circuit. As already mentioned the drift tube dimensions and shape are critical for the shunt impedance.

The rf field distribution, the geometries to reach the proper resonant frequency and the structure efficiency have been computed using SUPERFISH code for the generation of 40 cells at different energies. Figure 5 shows three representative geometries. In figure 6 are plotted the shunt impedance and the gap over cell length ratio along the linac. At every transition between the DTL segments the tank diameter is reduced, so that the gap length can be decreased keeping the resonant frequency and more space for longer quadrupoles is available.

The beam dynamics has been simulated with PARMILA code, using 1000 macroparticles and no losses have been seen; the beam profiles are shown in fig. 7.

For what the slow losses are concerned ($10^{-5}\div10^{-7}$) we can just say that, using the same frequency for the RFQ and the DTL and ramping the accelerating field at the beginning of the DTL, the beam dynamics in the whole injector should be comfortingly smooth. Moreover, operating in CW mode, the transients believed to be one of the main sources of slow losses at LAMPF are eliminated. Finally our bore radius is between 8 and 12 times the beam rms radius and this should be a safe value at these energies.

POWER CONSUMPTION AND EFFICIENCY

The performances of this linac, from the power consumption and power conversion efficiency point of view, are summarized in Table V.

*Table V :*Efficiencies

Beam current		10	30	50	50	mA (Peak)
Duty cycle		1	1	0.2	0.02	
Beam Power	P_b	1	3	1	0.1	MW
RF power diss.	P_d	9	9	1.8	0.18	MW
RF efficiency	η_{rf}	0.65	0.65	0.65	0.65	
Quad. Power	P_Q	0.6	0.6	0.6	0.6	MW
Power required	P_{AC}	16	19	5	1	MW
Efficiency	η	6%	16%	20%	10%	

The efficiency is defined as:

$$\eta = \frac{P_b}{P_{AC}} = \frac{P_b}{\dfrac{P_b + P_d}{\eta_{RF}} + P_Q}$$

with the symbols of Table V.

The power consumption is high, being a good fraction of the estimated power consumption of the 1 GeV linac. Increasing the length of the DTL one can gain in power, as shown in Fig.8, but this is reasonable only to a certain extend. The shunt impedance can be increased with a smaller bore hole radius of the drift tubes taking some risks concerning the beam losses. Different structures, such as CCDTL[7], have shown promising results at higher frequencies and they should be studied at 352 MHz. On the long term run it is worth the investigation for the development of superconducting structures even for this β range.

Finally in the last two columns of the Table V we considered the pulsed mode, that can be interesting in some moment of the commissioning of the linac, or for different applications, if the linac is built in a site as LNL where different users are present. In the first case the nominal 1 MW beam power is achieved in a more efficient way; in the second case a 100 kW beam, required for example for exotic beams production, is accelerated with reasonable efficiency. The acceleration of deuteron ions up to 100 MeV/u in pulsed mode should also be possible in the DTL.

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2. A.G. Ruggiero, “ A Superconducting Proton Linac as a Driver to the Energy Amplifier”, Brookhaven National Laboratory, 17th April 1996

3. C.Pagani, G. Bellomo, P. Pierini, “A High Current Proton Linac with 352 MHz SC Cavities”, to be published in the proceedings of the 1996 LINAC Conference, Geneva 26-30 August 1996

4. S.Ch. Joly, private communications.

5. J.Billen et al., Documentation of LANL accelerator design codes.

6. G. Amendola, J.M.Quesada, M.Weiss and A.Pisent. "Beam Dynamics studies for the CERN Lead-Ion RFQ" Proceedings of the third European Accelerator Conference, Berlin 1992, p.973

7. J. Billen et al., Proceedings of the 1994 International Linac Conference,Tsukuba, Japan, p.341.

Appendix A

Comparison with other existing and proposed DTL's.

Institution	Output energy	RF Frequency	Length	RF Power peak	Quadrupoles type	Duty cycle	ZT^2	Current peak	Ref.
ANL	50	200.06	33.5	3.5	DC	0.66	31.9	12	[A1]
FNAL	116	201.25	78	21	Pulsed	0.225	15.8	50	[A2]
LANSCE	~60	201.25	62	3	DC	1.242	30.7	11	[A3]
BNL	200	201.25	144	30	Pulsed	0.45	17.6	40	[A4]
KEK	40.3	201.069	28.4	3	Pulsed PMQ	0.55	33.5	18	[A5]
DESY	50	202.56	33.6	3.6	Pulsed	0.00625	38.2	20	[A6]
CERN	50	202.56	33.6	10	Pulsed	0.05	39.7	150	[A7]
ISIS	70.4	202.5	43	7	Pulsed	3.5	29.3	25	[A8]
ISTRA	36	297	16	7.3	PMQ	0.5	72.6	150	[A9]
SSC	70	427.617	24.33	2.7	PMQ	0.1	26.2	25	[A10]
EHF	150	400	74	13	DC	1	32	50	[A11]
This Note	**100**	**352**	**80**	**11**	**DC**	**100**	**20.8**	**30**	
	[MeV]	[MHz]	[m]	[MW]		[%]	[MW/m]	[mA]	

[A1] XVIII International Linac Conference Geneva, Switzerland Compendium of Scientific Linac p. 28.

[A2] Ibid. p. 30.

[A3] Ibid. p. 45.

[A4] Ibid. p. 53.

[A5] Ibid. p. 90.

[A6] Ibid. p. 133.

[A7] Ibid. p. 164.

[A8] Ibid. p. 173.

[A9] Ibid. p. 150.

[A10] Parameter Overview of SSC LINAC, 1992 Linear Acc. Conf. Proceed. Ottawa, Canada p. 323-328.

[A11] Proposal for a European Hadron Facility (EHF) Edited by J.F. Crawford. p. 176-180.

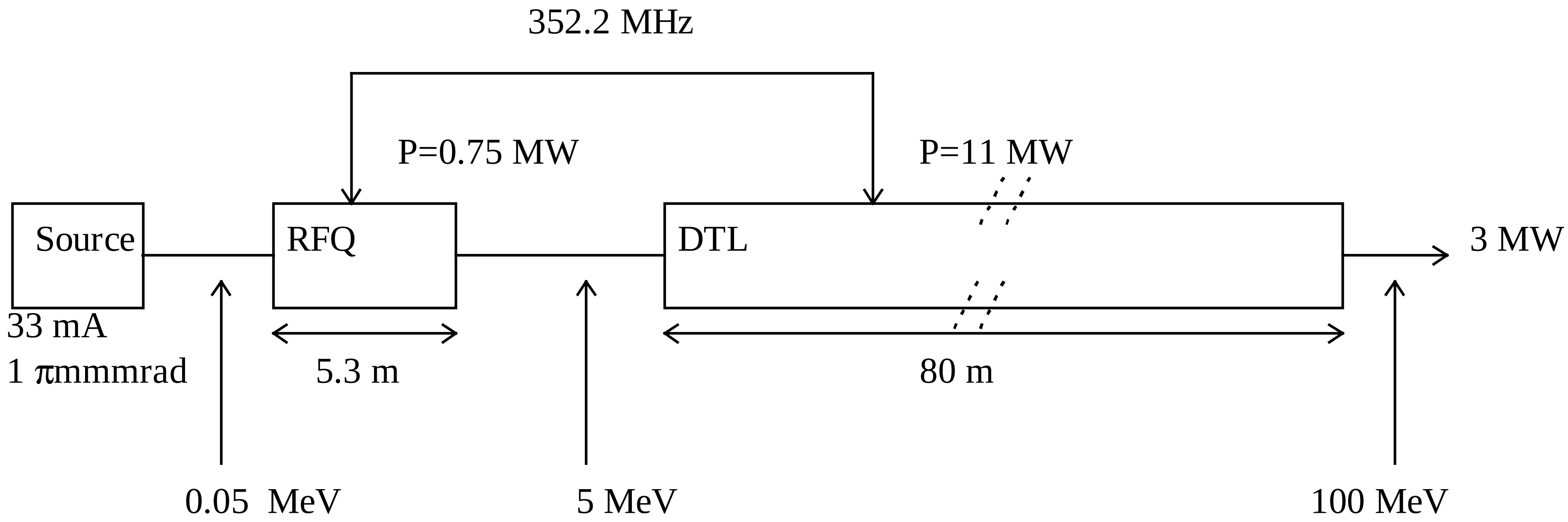

Figure 1: *Layout of the linac.*

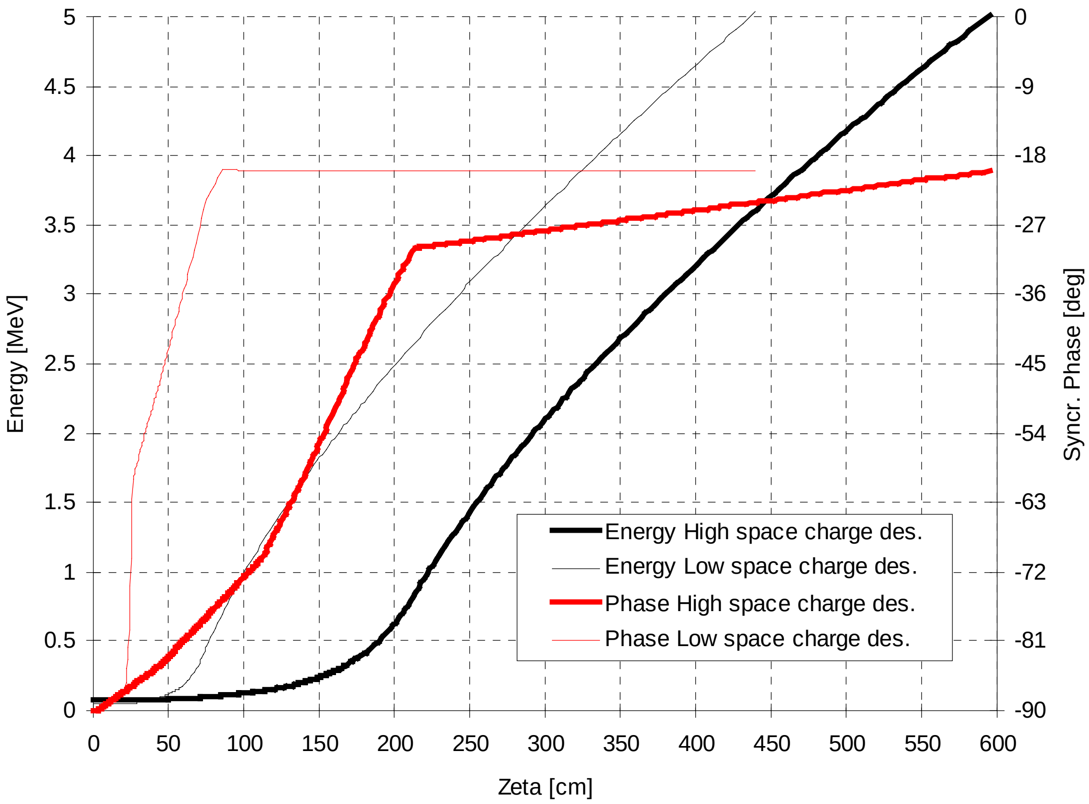

Figure 2: *Syncronous particle energy and phase in the RFQ as a function of length; high space charge and low space charge design technique are used*

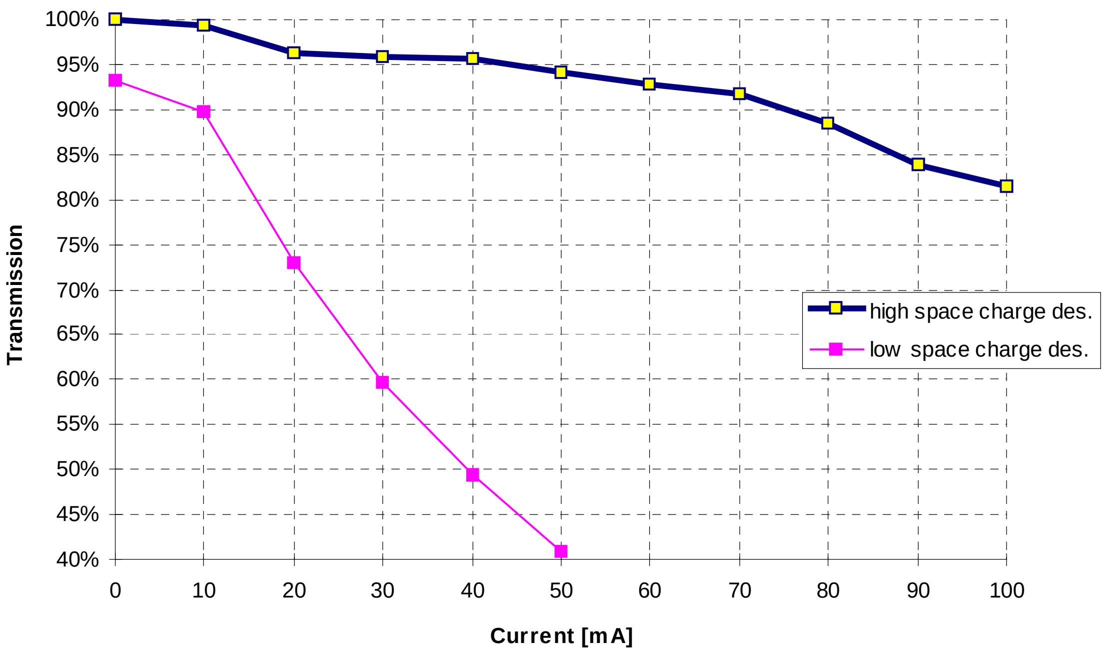

Figure 3: *RFQ transmission as a function of beam current for low space charge and high space charge design.*

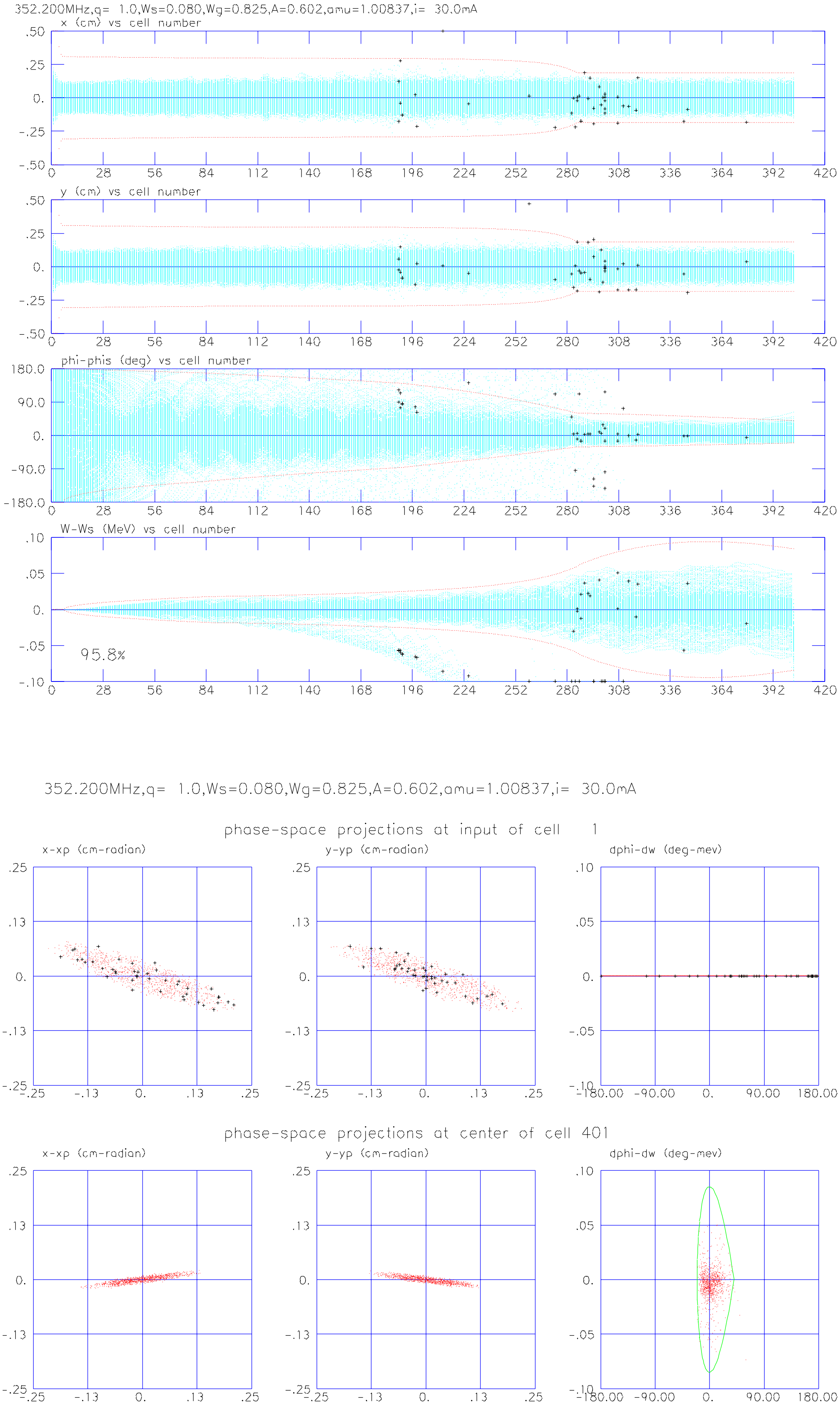

Figure 4: *Beam profiles,initial and final phase space in the RFQ (30 mA beam current)*

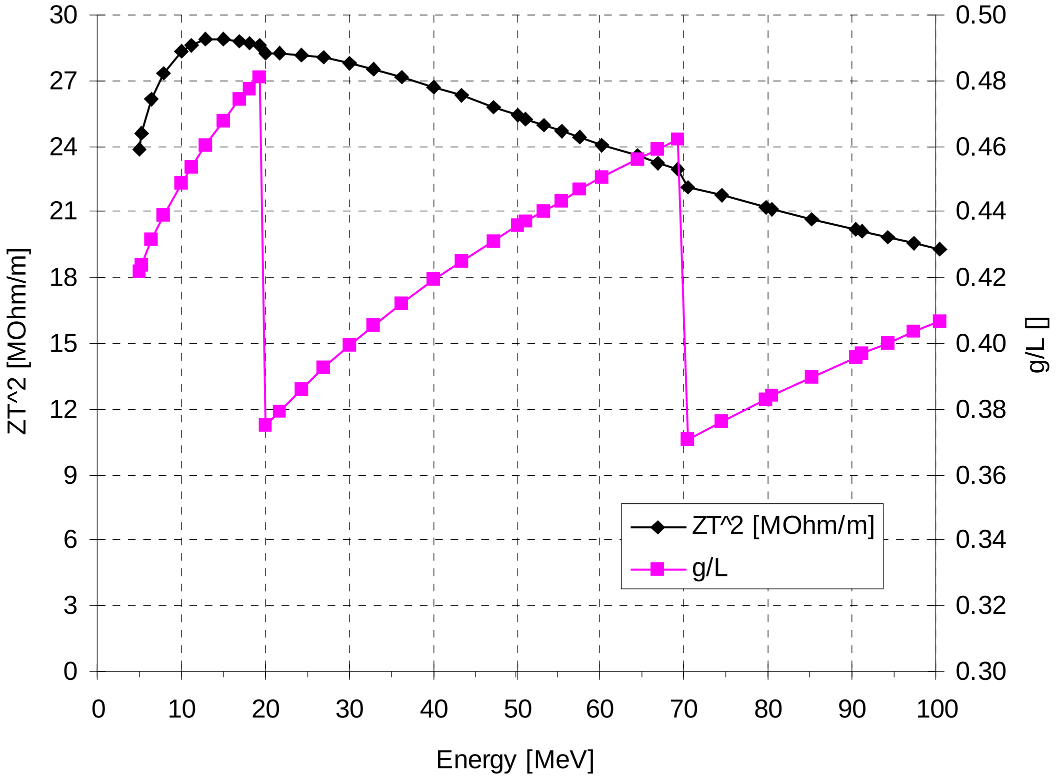

Figure 5: *Effective shunt impendance and gap over cell length ratio as function of energy in the DTL.*

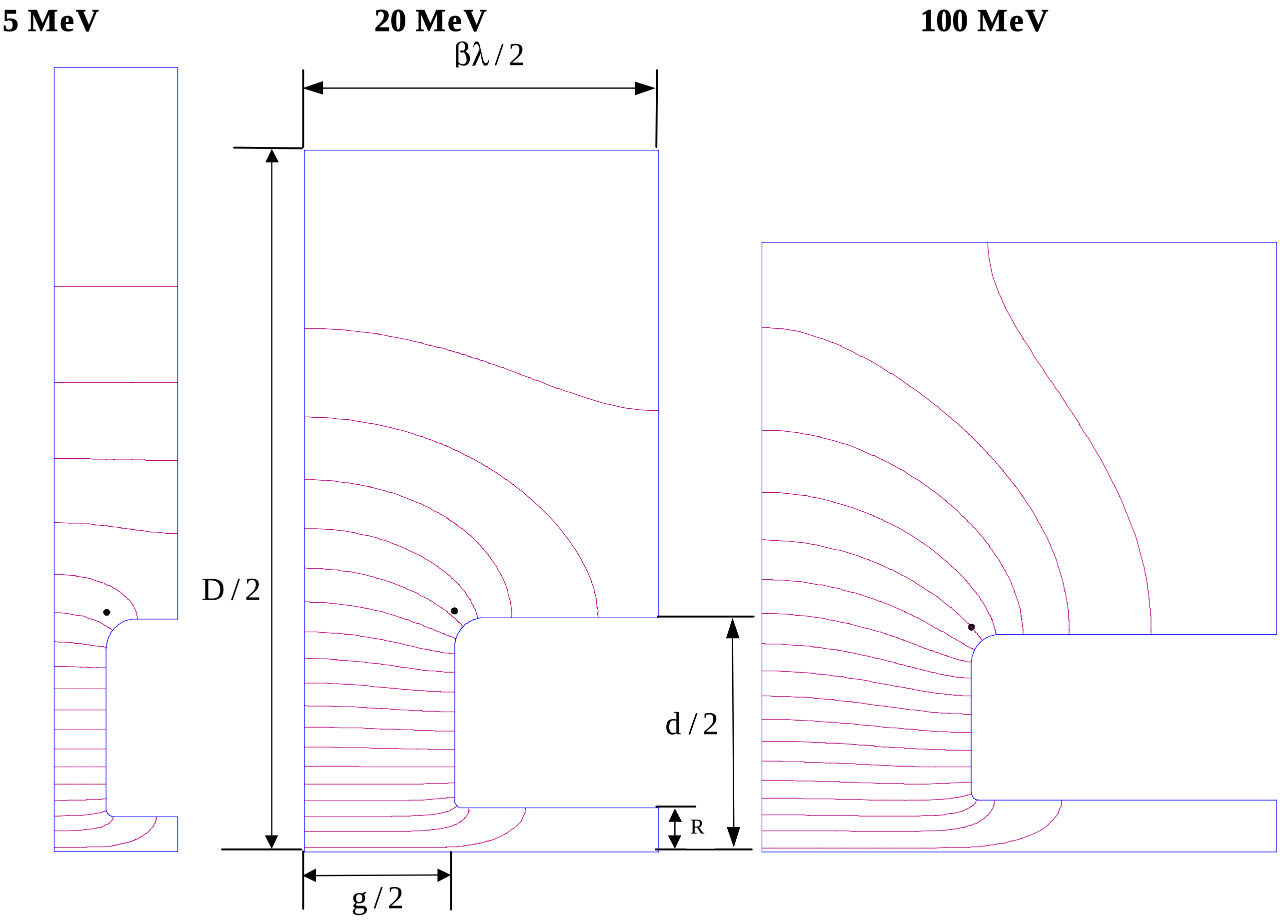

Figure 6: *Cell geometry and electric field for different energies in the DTL.*

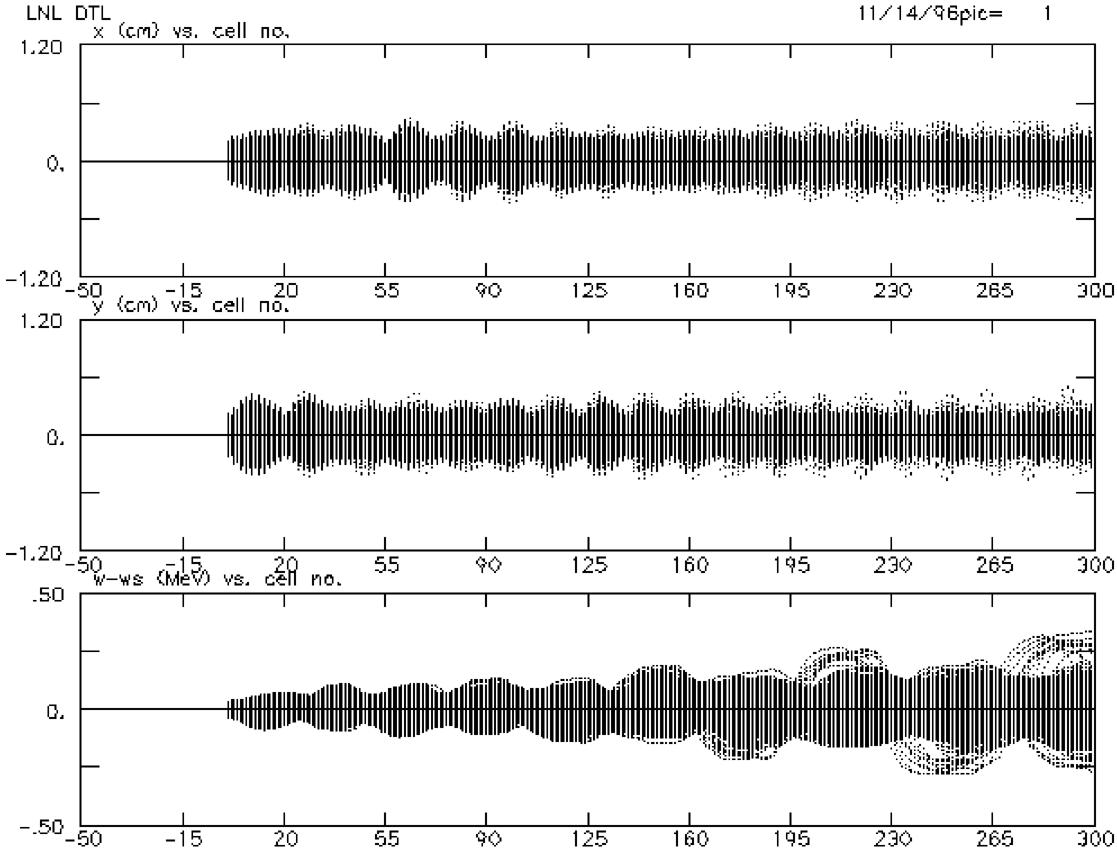

Figure 7:*Beam profiles in the DTL.*

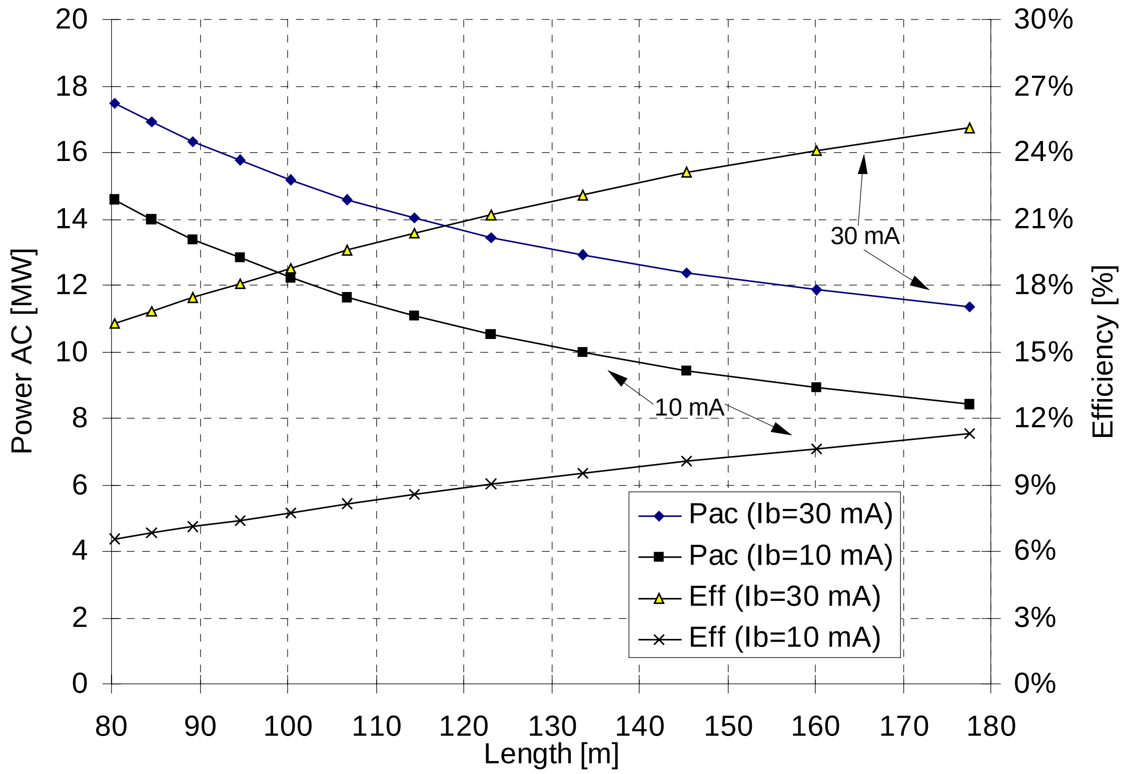

Figure 8: *Power consumption and power conversion efficiency as a function of DTL length, for 10 and 30 mA beam current.*