BEAM DYNAMICS ISSUES OF A 100 MEV SUPERCONDUCTING PROTON LINAC.

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Abstract

Proton linacs with beam intensities between 10 and 120 mA in CW are under study in various laboratories, for applications that go from fundamental physics to energy production and nuclear waste transmutation. The majority of those projects consider, for energy above 100 MeV, the use of a superconducting linac, which is particularly convenient for "moderate" currents (10-50 mA). For the low energy part the situation is unclear, and the advantages of a superconducting structure have not been generally recognized yet. In this paper we consider a possible architecture for a 100 MeV linac based on independently phased resonators, and we give a first analysis of the beam dynamics issues, and the resulting cavity specifications. The flexibility of such a linac, for the use with different charge over mass ratios and beam currents, will be underlined.

1. Introduction

There is at present operational experience with two kinds of superconducting accelerating structures: multi-cell elliptical cavities for relativistic electrons and short cavities (with more complex geometry like inter-digit and quarter wave..) with few accelerating gaps for slow heavy ions. The recent interest for high intensity proton linacs has pushed the research of a possible superconducting proton linac. [1][2][3]

Such a linac clearly happens to fall between the two mentioned kind of superconducting linac; in particular above 100 MeV (β=.43) the use of modified elliptical cavities is under study. For the low energy part, after the RFQ (3 MeV, β=.08), the use of cavities similar to those used for heavy ions could be conceived. Development of cavities for this kind of applications has been done mainly at ANL, [4][5] but other studies can be found in literature. [6]

In this paper we show a preliminary analysis of a different approach; we use independently phased resonators with two accelerating gaps and operating at 176 MHz (half of the European choice for the main linac). These resonators could be similar to the cavities used for ALPI. [7]

Our attention is centered on beam dynamics issues: we determined a preliminary set of parameters for a ISCL (Independent Superconducting Cavity Linac) that could help in cavity development. On the other hand the work we did to adapt the classical chain of LANL programs (PARMTEQM, PARMILA…) [8] to this specific problem will be useful when the technological inputs (from cavities, magnets, cryostats, RF systems……) will be more clear.

Table I : Beam Specifications.

Kind of particle	p	
Output energy	100	MeV
Duty Cycle	100	%
Beam current	10	mA
RMS normalized beam emittance	0.2	π mm mrad

Table II Main parameters of the Linac (10 mA beam current).

		RFQ	ISCL
Input Energy	MeV	0.075	3
Output Energy	MeV	3	100
RF Frequency	MHz	176	176
Total Length	m	3.38	71
Transmission	%	98.0	100.0
Output RMS Emittance			
ε_x Normalized Horizontal	π mm mrad	0.2	1.2
ε_y Normalized Vertical	π mm mrad	0.2	1.2
ε_L Longitudinal	MeVdeg	0.2	0.2
RF power dissipation	kW	220	1.5 (@2 K)
Beam loading	MW	0.03	0.97
RF System Power Consumption	MW	0.44	2
Cryo System Power Consumption	MW	-	1.5
Quadrupoles and ancillaries	MW	-	1
Mains Power	MW	0.44	4.5

2. The RFQ.

For the accelerator front end we have considered a proton source, followed by an RFQ. The beam matching at RFQ entrance can be guaranteed by two solenoids. 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 with an operating frequency of 200 MHz. The optimization design techniques available for the RFQ's are indeed depending on the beam current intensity and RF frequency because of the space charge forces. In the case of high space charge 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 [9], and has also been applied in this case.

Table III RFQ parameters.

Beam current		50	10	mA
Input Energy	Wi	0.075		MeV
Average radius	R_0	6.0		mm
Minimum aperture	a	2.8		mm
Synchronous phase	ϕ_S	-90÷-21		deg
Modulation coefficient	m	1÷3		
Adjacent vanes voltage	V	119		kV
Maximum surface field	E_S	27.2		MV/m (1.9 E_{KP})
Output RMS Emittance	ε_x N	0.2	0.2	π mm mrad
	ε_y N	0.2	0.2	π mm mrad
	ε_L	0.15	0.2	π MeVdeg
Current limit (90% transmission)	I_{max}	75		mA
Length		3.38		m
Transmission		96	98	%
Frequency	f	176		MHz
Stored Energy		2.8		J
Beam loading		30	150	kW
Dissipated Power	P_d	210	210	kW
RF Power	P_{rf}	360	240	kW
Output Energy	W_{out}	3		MeV

The resonator type for a RFQ operating at 176 MHz can be a four-vane structure. The cavity length is about twice the RF wavelength in the free space and consequently particular care has to be put in the stabilization of the field distribution with a suitable field stabilization 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 65 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.

As an alternative a superconducting RFQ [10] can be thought, both in bulk Nb e-b welded or in Nb sputtered over Cu. For example the model under development ad LNL for the sputtering technique resonates at 160 MHz and has an average aperture R_0=7.5 mm. [11] The resonator is not a four vanes but a 2:1 scaled model of the resonator chosen for PIAVE (symmetric four roads). [12] These parameters are not far from those of table III, but many problems are more severe than in heavy ion case. For example the RF powering with high beam loading and stored energy, the surface pollution in the presence of the big gas loading from the source, are all problems to be solved. For this reason we kept the normal conducting option in the nominal design summarized in Tab. II.

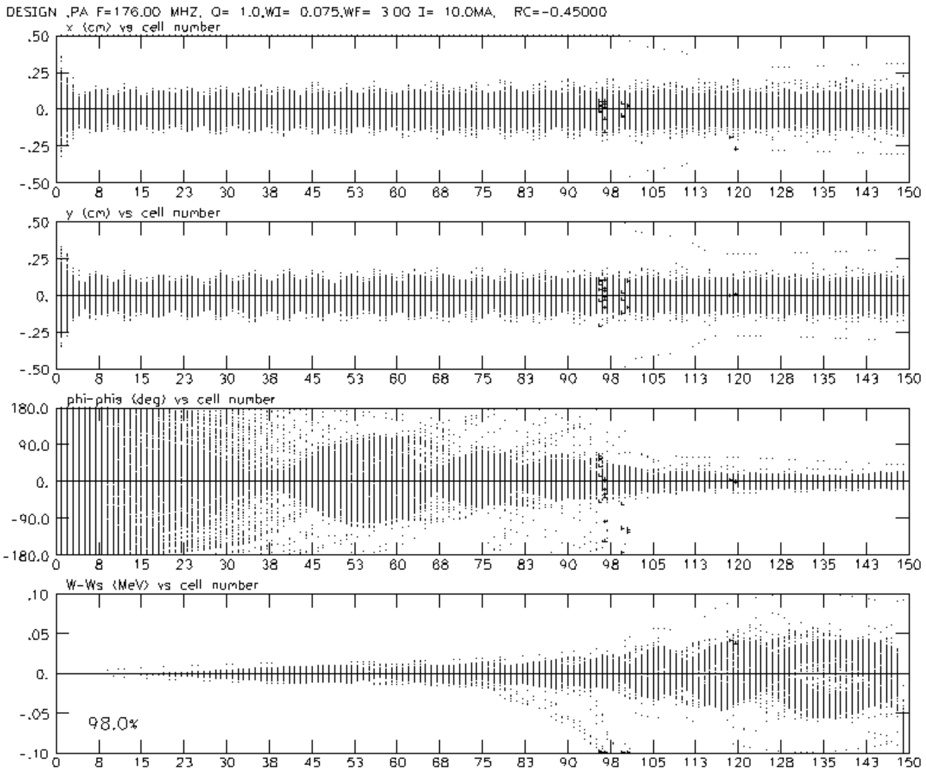

Figure 1 *Beam profiles in the RFQ (10 mA).*

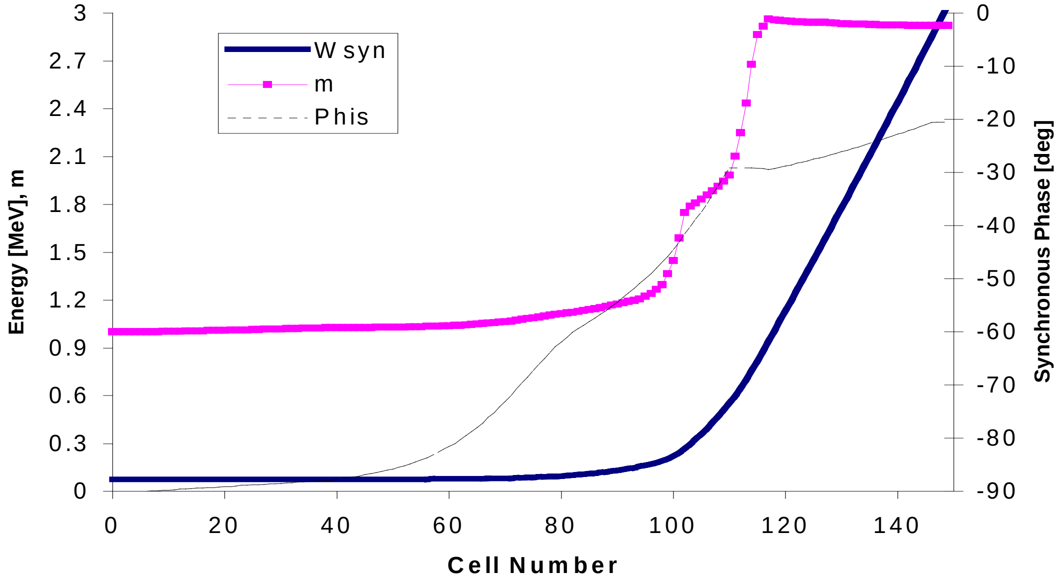

Figure 2 *Energy, Synchronous Phase, and modulation parameter inside the RFQ.*

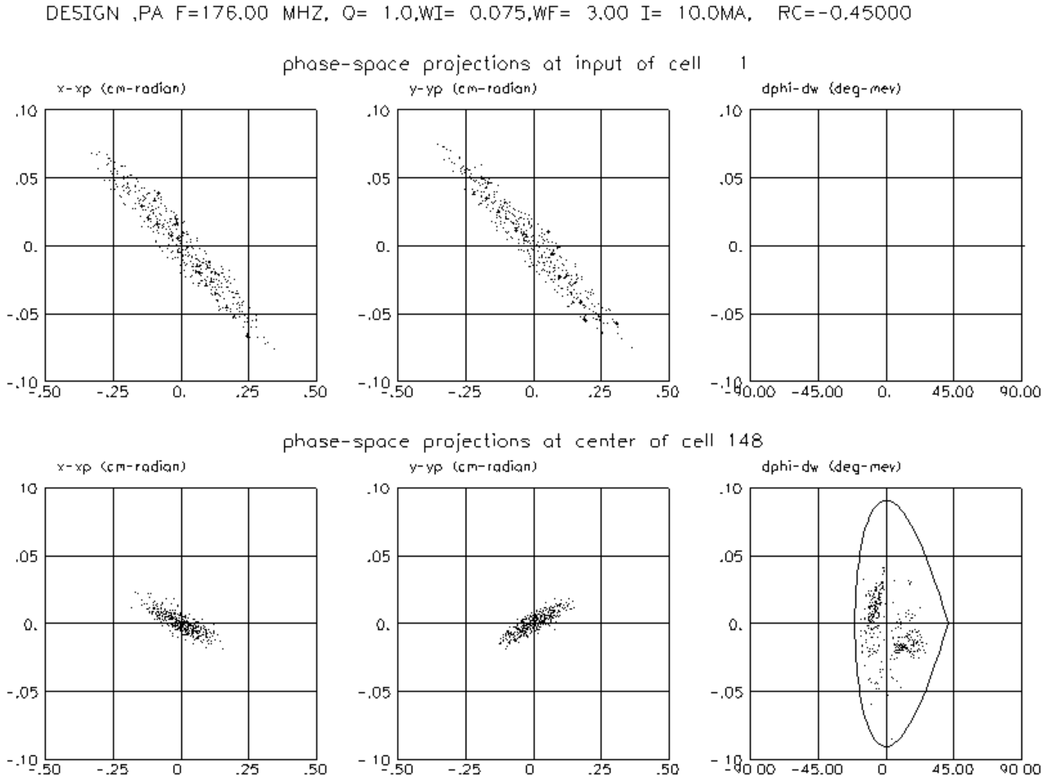

Figure 3 *Phase planes at the RFQ input and output.*

3. The ISCL

The energy range between 3 and 100 MeV is generally covered by a normal conducting structure of DTL kind (Alvarez linac). The design of a 352 MHz DTL for our applications is considered in ref. [13], and will be used for comparisons. We have here instead considered a superconducting linac, using several two gap independently phased resonators. The distance between the two gaps of each cavity is correct (for mode π acceleration) only at the nominal velocity β_0, so that in the whole energy range the acceleration is multiplied by a transit time factor less then one. In our design the use of just two kinds of cavity guarantees a transit time factor bigger then 0.8 all over the linac (fig. 4). As in heavy ion linacs the phase of each cavity is tuned in such a way that the reference particle crosses the center of the cavity with the synchronous value of the phase (-30^0 in our case).

The resonator characteristics are listed in Tab. IV. They can be both $\lambda/4$ or $\lambda/2$ kind; the aperture is very large, compared to heavy ion linacs, and this is clearly due to beam dimensions and beam dynamics issues. What indeed characterizes this linac respect to its heavy ions cousins is the importance of space charge and the necessity of avoiding even very small losses due to activation risks.

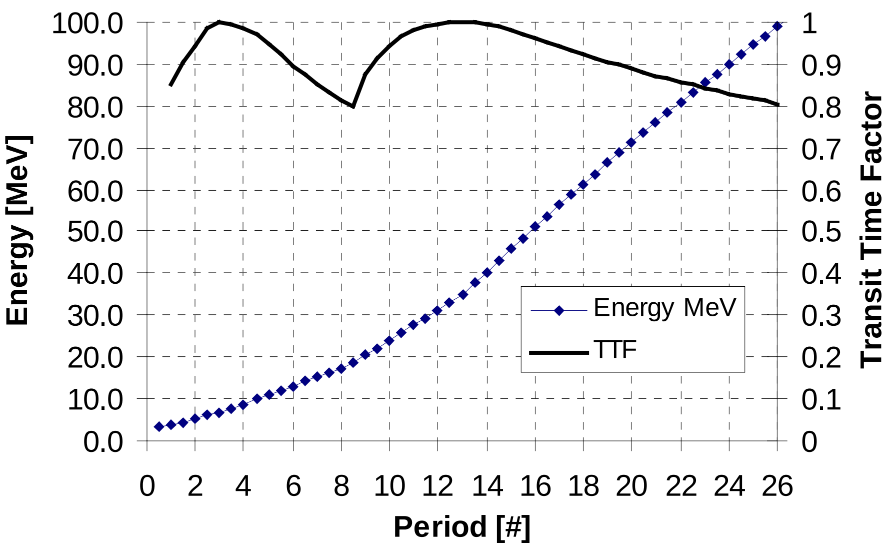

Figure 4 *Transit Time Factor and beam energy as a function of period number.*

We have chosen a FODO focusing structure with period 6βλ, as shown in Fig. 5; β is the reference velocity in the period. As the period becomes longer a larger number of cavities can be installed between the quadrupoles. This design gives the advantage of an almost constant quadrupole gradient (about 10 T/m) and beam envelope in the whole energy range. The zero current transverse phase advance per period is 75^0. Moreover the adiabatic increase of the period makes easier the beam matching at the two extremes. Indeed the RFQ has a very short period (βλ) and the superconducting main linac has a period of more than 10; the matching transport lines in both cases are a very critical issue and have not yet been attached. Finally at 100 MeV the frequency jump to 352 MHz has to be performed; for this reason a particular care has been spent in the longitudinal emittance preservation in the ISCL.

The quadrupole parameters (shown in Tab. V) can be reached both by normal conducting and superconducting quads. Nevertheless, due to the lack of space, it is probably necessary to use superconducting quadrupoles installed inside the same cavity cryostat. A cost-effective design of such weak superconducting quadrupoles, and the shielding of their field respect to cavities, are open points of this preliminary design.

Table IV ISCL cavities characteristics.

# of gaps	2	2	
β_0	0.108	0.25	
Bore aperture ϕ	60	60	mm
L_{eff}	¾ βλ=138	¾ βλ=319	mm
beam loading	2.7	6.2	kW
E_a (nom. current)	2.6	2.6	MV/m
E_a (low beam load)	5.2	5.2	MV/m
power dissipation	~10	~10	W (@2K)

Table V ISCL quadrupole characteristics.

Bore aperture ϕ	80	mm
L_{eff}	100	mm
max gradient	15	T/m

The linac has been simulated with PARMILA, using 1000 macro particles and about 400 elements. Each cavity is represented by an accelerating gap. The structure of the linac, following the scheme of fig. 5 and Tab. VI, is generated by an EXCEL workbook that writes the input file for PARMILA and reads the results preparing automatically several plots.

The main source of troubles for the beam dynamics is the period length. For the same beam current, emittance and focusing strength a longer period determines a stronger influence of space charge. This results in a larger tune-shift, beam envelope dimension and energy-dependence of the beam envelop. In Fig. 6 are sketched these dependencies in smooth approximation. In other words the necessity of a long period, able to host the cavities, makes the transverse dynamics rather weak, and even 10 mA of beam current, that for the DTL of ref. [13] were very easy to transport, are at the space charge limit.

Moreover the periodicity is broken by the change of cavity number and period, that is not an adiabatic process. For this reason it is impossible to avoid a certain beam mismatch and consequent emittance increase. In fig. 7 the beam envelopes and emittances along the linac are plotted. In fig. 8 we show the final phase planes.

For what the slow losses are concerned this linac shows some weakness, and relative losses of the order of 10^{-4} (of the order of the 1 μA) seems very difficult to avoid with this design. Moreover the impact of mechanical errors has not yet been evaluated.

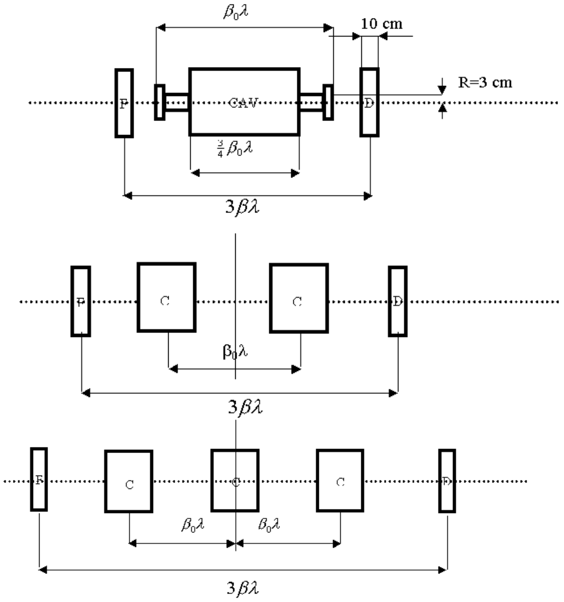

Figure 5 *Geometry of half period of the ISCL.*

Table VI ISCL structure.

Energy Range [MeV]	Cavity/period	β_0	# of Periods*	# of Cavities
3 ÷ 3.7	2	0.108	1	38
3.7 ÷ 7.6	4	0.108	3	
7.6 ÷ 17.0	6	0.108	4	
17.0 ÷ 34.9	4	0.25	5	98
34.9 ÷ 100	6	0.25	13	
Total			26	136

*The Number of quadrupoles is twice the number of periods.

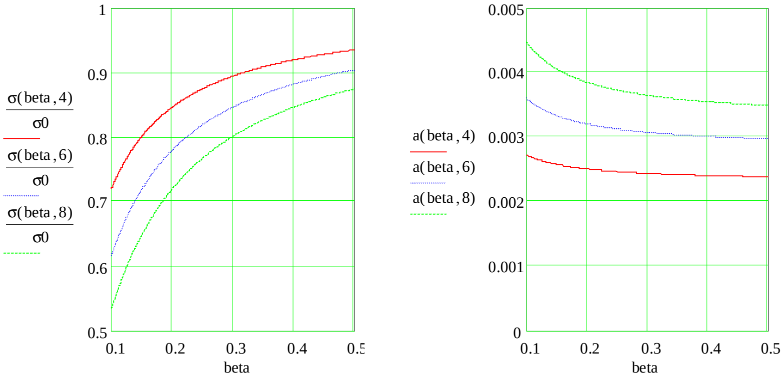

Figure 6 *Tune depression σ/σ_0 and beam envelope(in m) as function of the reference velocity β for $n\beta\lambda$ period length (n=4,6,8). Calculation are performed for a matched smooth beam; σ is the space charge depressed phase advance per period, σ_0 (~75 deg) is the zero current phase advance. These two values corresponds to those calculated for our nominal optics.*

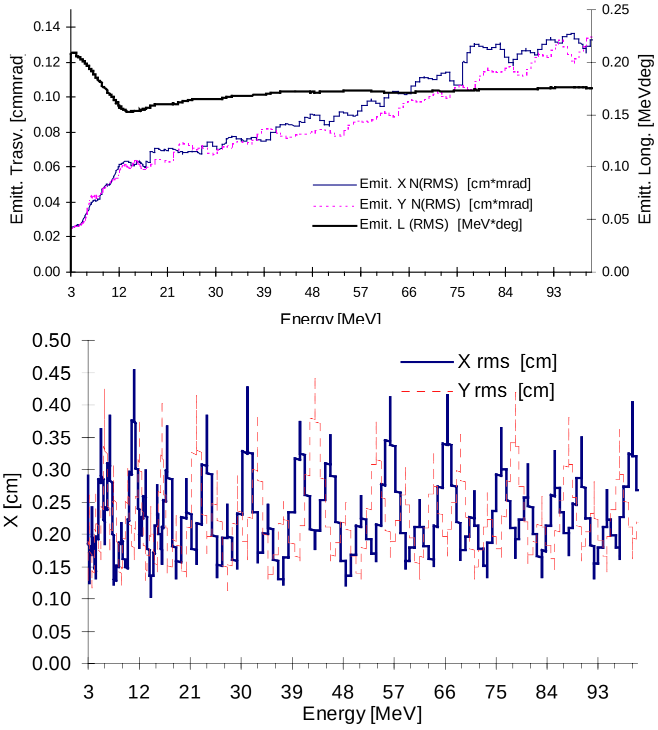

Figure 7 *Emittances and RMS envelopes in the ISCL.*

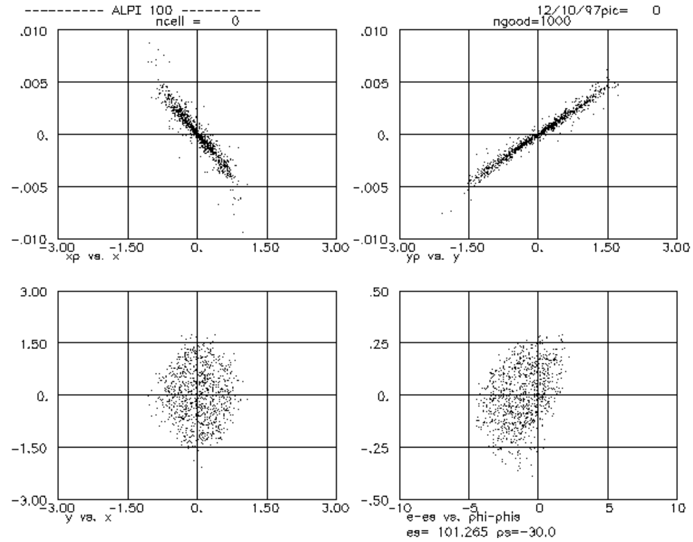

Figure 8 *Output phase planes of the ISCL; lengths are in cm, divergences in rad, phase angles in degree, energies in MeV.*

4. Different modes of operation of the ISCL.

In the ISCL 136 independent RF chains feed the 136 cavities, in CW mode. Following the heavy ion linac experience very reliable RF systems can be realized using solid state amplifiers. For each cavity the power dissipated is very small (about 10 W), the reflected power needed for phase locking is of the order of the kW, the main part of the power goes in beam power. We have assumed a maximum power of 10 kW per amplifier; the amplifier performances limit the accelerating field to 2.6 MV/m for the nominal 10 mA beam.

This architecture, respects to a traditional DTL, has the advantage of the considerable flexibility, and allows:

1. the compensation of the lack of performance of some cavities with the adjacent ones;
2. the use of the linac, with reasonable efficiency, at lower intensity keeping the CW characteristic of the beam;
3. if the linac is used as stand alone at low current (~1 mA) the field can be increased so to get almost 180 MeV of final energy;
4. a moderate current of particles with *q/A*= ½ can be accelerated up to a final energy of 100 MeV/u.

Table VII Comparison between ISCL and DTL for different modes of operation.

	ISCL			DTL [13]			
Particle	p	p	d	p	p	p	
Duty cycle	1	1	1	1	.2	.02	
Peak Current	10	1	<1	10	50	50	mA
Final energy	100	180	100	100	100	100	MeV/u
Beam Power	1	0.180	<0.2	1	1	.1	MW
Mains Power	4.5	3.5	3.5	16	5	1	MW
Efficiency	22%	5%	<5%	6%	20%	10%	

In table VII these kinds of operation are summarized, and some parameters are compared with the DTL design. In doing this we have assumed a 50% power conversion efficiency for the RF system, and 10^{-3} power conversion efficiency for the cryogenic system. Both estimates are reasonably relaxed. The resulting estimations of the power consumption of the facility are indicative (probably affected by a 20% error).

5. Conclusions

We have designed a 176 MHz superconducting linac, able to accelerate a 10 mA CW beam up to 100 MeV, to be injected in the superconducting linac of a waist transmutation driver, but also able to accelerate, with good efficiency, 1 mA up to 180 MeV CW, as required for exotic beams production. Many points of this design work are very preliminary, but could be used as a base for cavity R&D.

6. Acknowledgements

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