A 100 MeV SUPERCONDUCTING PROTON LINAC: BEAM DYNAMICS ISSUES

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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 the 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

The interest for a superconducting proton linac covering the traditional DTL energy range has recently grown, in connection with various high intensity linac studies. We considered in this paper an Independently phased Superconducting Cavity Linac (ISCL) similar to those used for low energy heavy ions in many nuclear physics laboratories like ours, but at much higher beam intensity, and in a wider beta range. Development of cavities for this kind of applications has been done mainly at ANL[1], and other studies can be found in literature[2]. The high power coupler design and the beam losses control are specific problems related to the high beam power.

We show here a preliminary analysis at 352 MHz. Our attention is centered on beam dynamics issues: we determined a preliminary set of parameters that could help in cavity development. The classical chain of LANL programs (PARMTEQM, PARMILA…) was adapted to this specific problem so to have results based on well proven codes (especially for what space charge and initial distributions are concerned). We checked various approaches, like single and double gap cavities, 176 MHz and 352 MHz [3].

The most promising design for 30 mA beam current is based on the so-called “reentrant cavities”, that are modified pillbox, cylindrically symmetric and therefore theoretically dipole free.

2 THE ISCL

The linac was designed taking the main beam parameters used for TRASCO, the INFN-ENEA feasibility study for a waste transmutation Accelerator Driven System (ADS). In Tab. I we list the main specifications and the beam characteristics from the 352 MHz 5 MeV RFQ, with some emittance dilution in the matching line[4]. In the last two rows we specify the two main constraints of the independently phased resonators: the surface field and the beam loading per cavity. In particular the second constraint is specific of high current machines: in our case we want to feed each cavity with a single solid state amplifier and the limitation to 15 kW seems consistent with the present technology.

Table I: Main specifications of the linac.

Particle species		p	
Input energy		5	MeV
Output energy		100	MeV
Beam Current		30	mA
Duty cycle		100%	
Input RMS Emittance	Trans (norm)	0.4	mmmrad
	Long.	0.2	MeVdeg
Frequency		352	MHz
Maximum beam loading/cavity		15	kW
Maximum surface field		25	MV/m

3 THE REENTRANT CAVITIES

Various kind of superconducting resonators were developed or proposed for this β-range. Among them an attractive choice is a modified version of the reentrant cavities developed at Stanford [5]; in this early work the feasibility of low-β, single-gap niobium structures with good RF performance and no serious multipacting problems was demonstrated [6]. At the frequency of 352 MHz and in the presence of a relatively large bore, these cavities present many advantages: the axially symmetric shape avoids dipole field components; the single gap guarantees the widest velocity acceptance and the possibility of covering the full interval from 5 to 100 MeV with only one type of resonator; the simple geometry, which requires very few electron beam welds, allows for a low construction cost in the view of mass production. The maximum field achievable in superconducting cavities is usually limited by the onset of field emission; single gap structures, then, could appear less attractive than multigap, high shunt impedance ones. However the relatively low energy gain per cavity which is required in our linac design and the low surface electric field ratio E_p/E_a of reentrant cavities make them perfectly adequate to the aim. The ISCL resonator characteristics, calculated by means of the program SUPERFISH, are listed in Tab. II. In fig.1 the shape of the new resonators and the design of the Stanford cavity are shown.

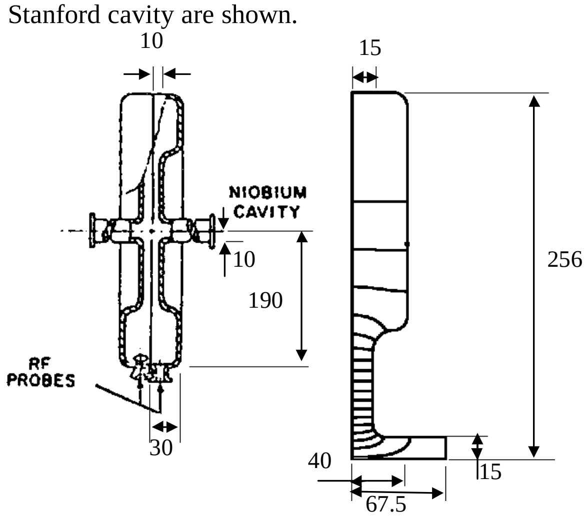

Figure 1: Reentrant cavity: the Stanford cavity (430 MHz [6]) and the proposed ISCL geometry (352 MHz).

Table II: Main cavity parameters (SUPERFISH).

Effective length	80	mm
Effective gap	53	mm
E_p/E_a	3.01	
H_p/E_{a}	32	Gauss/(MV/m)
$\Gamma=R_s\times Q$	82	Ω
R'_{sh}/Q	18	kΩ/m

4 BEAM DYNAMICS

We have chosen a FODO focusing structure with period 6βλ. 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 and beam envelope in the whole energy range. The zero current transverse phase advance per period is about 55 deg and the initial depressed one 45 deg. Moreover the adiabatic increase of the period makes the beam matching easier at the two extremes, with the RFQ and with the main linac.

The quadrupole parameters can be reached both by normal conducting and superconducting quads. Nevertheless, due to the lack of space, it is necessary to use superconducting quadrupoles installed inside the same cavity cryostat. A cost-effective design of such magnets is an open point.

The preliminary power consumption figures in Table III are rather conservative.

Table III: ISCL Parameters (30 mA).

Total length		65	m
Synchronous phase		-30	deg
Average acceleration		1-1.8	MeV/m
Number of cavities		253	
Cavity bore radius		1.5	cm
Quadrupole gradient		30	T/m
Quad aperture/length		2/5	cm
Output RMS Emittance	Trans. (nor)	0.6	mmmrad
	Long.	0.2	MeVdeg
Current limit (losses<10^{-4})		>50	mA
RF dissipation (R_s=100nΩ)*		890	W(@4.5)
Beam loading		2.85	MW
RF sys. pwr. cons. (η_{RF}=50%)		5.7	MW
Static cryo. losses (10 W/m)		650	W
Cryo. sys. cons. (η_{cryo}=1/500)		0.8	MW
Quadrupoles and ancillaries		0.5	MW
Mains power		7	MW
Pwr conversion efficiency		41%	

Table IV: ISCL Structure.

Energy [MeV]	Cavities/period	# of Periods	# of Cavities
5 ÷ 12.5	1	23	23
12.5 ÷ 28	2	30	60
28 ÷ 30	3	4	12
30 ÷ 55	3	18	54
55 ÷ 100	4	26	104
	Total	101	253

The linac has been simulated with PARMILA (standard PC version), using 10000 macro particles and about 700 elements (concatenated runs). Each cavity is represented by an accelerating gap. The structure of the linac, following the scheme of Tab. IV, is generated by an EXCEL workbook that writes the input files for PARMILA and reads the results preparing automatically several plots.

In Fig. 2 (upper part) the most significant parameters are plotted as a function of length. The transit time factor is in the range 50-98%. The voltage per cavity is chosen as to maintain a constant energy gain per linac length in the two linac parts; from the W plot the first (about 1 MeV/m) and the second (about 1.8 MeV/m) part of the linac can be distinguished. The plots of the surface field and of the energy gain per cavity show that the constraints are fulfilled.

In Fig. 2 (lower part) we plot the RMS envelopes, less then 1/7 of the aperture, and the emittances. Due to the non adiabatic change of the period structure some residual mismatch cannot be avoided. The emittance increase is acceptable, and can be partly seen heuristically as an exchange of energy (equipartitioning) between the longitudinal and the transverse degree of

* The BCS resistance is 58 nΩ.

freedom. The transverse degree of freedom is colder because the ISCL period is 6 times the RFQ period.

We have simulated currents up to 50 mA , and we did not see losses (10000 macro particles). Smaller losses must be investigated by other means.

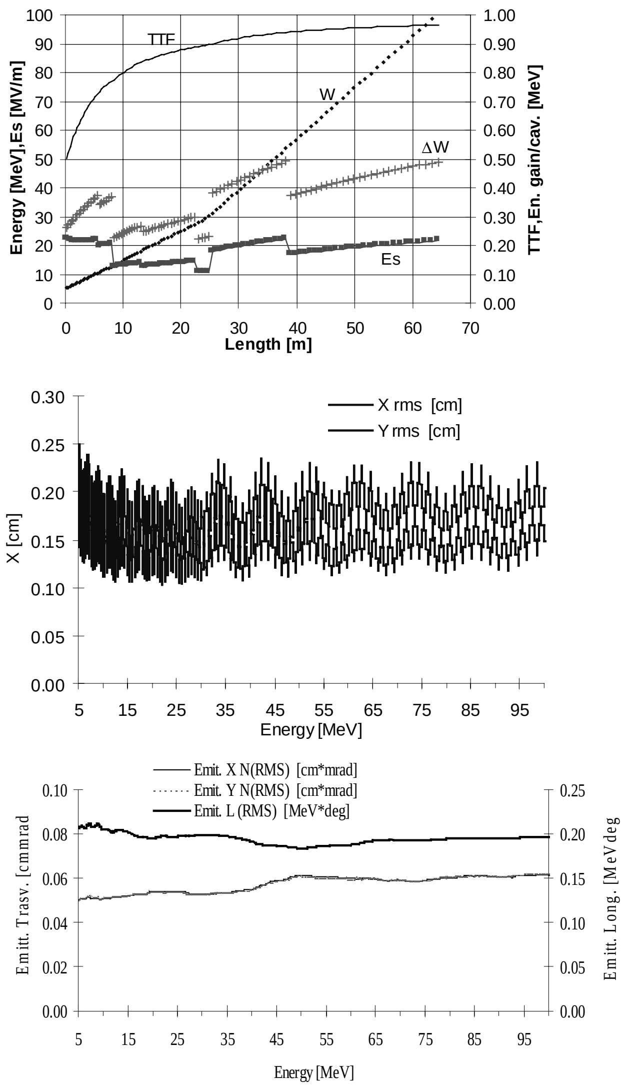

Fig. 2: Linac parameters as a function of position, RMS envelopes and Beam Emittance as function of energy.

5 DIFFERENT MODES OF OPERATION

The ISCL, in addition to a lower power consumption, has, with respect to a traditional DTL, the advantage of a considerable flexibility. It allows (see Tab. IV):

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 140 MeV of final energy (Exotic Beam production);
4. A moderate current of particles with q/A= ½ can be accelerated up to a final energy of 70 MeV/u.

Table IV: ISCL Operation modes (CW).

Particles	p	p	d	
Peak Current	30	1	<1	mA
Final energy	100	140	70	MeV/u
Beam Power	3	0.14	<0.15	MW
Mains Power	7	2	2	MW
Efficiency	41	7	7	%

6 CONCLUSION

We have designed a 352 MHz superconducting linac, able to accelerate a 30 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 140 MeV CW, as required for exotic beams production. Single gap axially symmetrical cavities (with a single design in the whole energy range) have been used. Many points of this design work are preliminary, but can be used as a base for cavity R&D.

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