Study of Beam Transport and Dynamics in the ARES SC Linac

S.Bartalucci, C.Biscari, L.Palumbo°, B.Spataro

INFN, Laboratori Nazionali di Frascati, C.P.13, 00044 Frascati, Italy
° Dip. Energetica Univ. Roma 'La Sapienza', V. A. Scarpa 14, 00161 Roma, Italy

Abstract

The optical structure of the SC Linac and corresponding recirculation arcs is designed to optimize the acceleration and transport of both e+ and e- beams up to an energy of 440 MeV. The effects of wakefields excited in the SC cavities are studied and taken into account in the design. Single bunch instabilities are carefully analyzed, being of primary importance in current limitation and emittance preservation for such machines. A thorough calculation of Higher Order Modes (HOM) has been done in order to investigate multibunch instabilities.

Introduction

The SC ARES linear accelerator consists of two sections[1](Fig.1). In Section L1 four SC cavities provide an energy gain of 1.2*g each, g being the average accelerating gradient. A value of 10 MeV/m is aimed at. The input energy is E_{i1} = 8 MeV and the output energy is E_{f1} = 56 MeV. Each four-cell SC cavity has its own cryostat and constitutes a cryomodule.
In Section L2 there are 16 similar four-cell cavities. Since less focusing is needed to control the transverse beam dynamics, the cryostat can accomodate two cavities. The overall output energy is E_{f2} = 248 MeV. The beam can be recirculated through Section L2 achieving a maximum energy of 440 MeV.

Linac focusing

The focusing along the Linac is provided by a FODO sequence of 0.2 m long quadrupoles, one per cryomodule.The distance between quadrupoles is 3 m in L1 while the focusing can be made weaker on L2, and the half FODO cell is therefore lengthened to 5.4 m to fit the longer cryomodule.
In the first two cavities of Section L1 the energy gain is larger than the initial energy so that the effect of the RF accelerating field on the beam transverse optical functions is not negligible, therefore a careful analysis of beam dynamics is needed [1,2]. Hence the FODO lattice focusing is highly perturbed and a strong mismatch occurs and proper corrective action has to be taken. Both the input betatron functions and the quadrupole strengths must be modified in order to compensate for the RF cavity effects. Thus, a FODO sequence of sligthly different cells is used

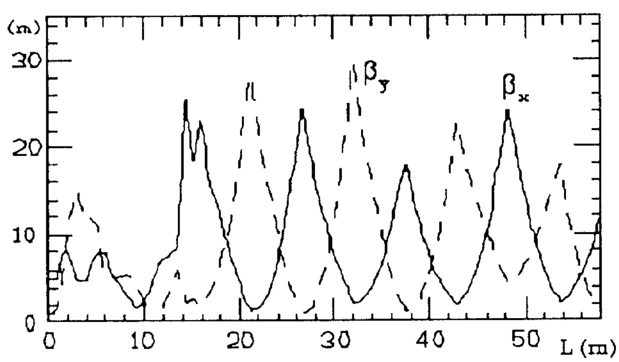

Fig.2 - Betatron functions along linac L1, matching section and linac L2. Initial energy = 8 MeV; final energy = 248 MeV.

such to guarantee the matching between the linacs. The proposed lattice for Section L2 is still a standard 120° phase advance FODO with some adjustment of the quadrupole field to match the betatron functions; the cell is 10.8 m long to accomodate the cryomodule. The average quadrupole strength is reduced to 1.6 m^{-2}, corresponding to a maximum gradient of 1.5 T/m. A triplet matches the optical functions between the linacs L1 and L2. Figures 2 and 3 show the optical functions and the beam transverse dimensions along L1, the matching section and L2.

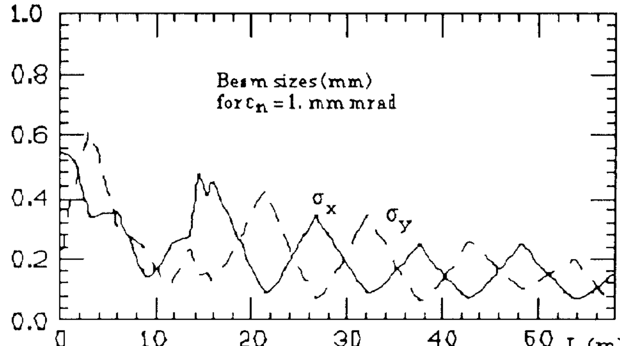

Fig.3 - Beam transverse sizes along linac L1, matching section and linac L2 for a normalized emittance of $1x10^{-6}$ m rad. Initial energy = 8 MeV; final energy = 248 MeV.

Figures 4 and 5 show the optical functions and the beam transverse dimensions on the second passage. The two transverse planes are of course interchangeable.

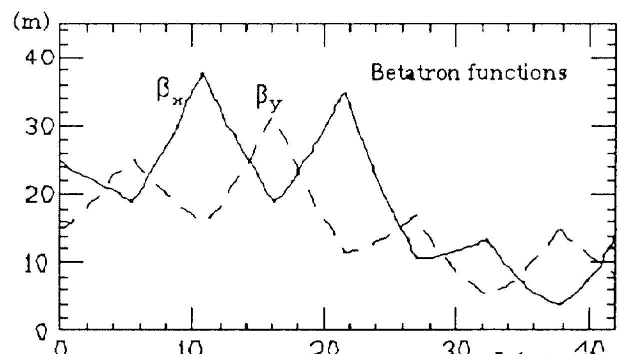

Fig.4 - Betatron functions along linac L2 on the second passage. Initial energy = 248 MeV; final energy = 440 MeV.

Although in the second passage through L2 the beam sees a weaker focusing field, the beam sizes are nevertheless smaller than the design value of 0.3 mm ($\varepsilon_n \approx 1x10^{-6}$).

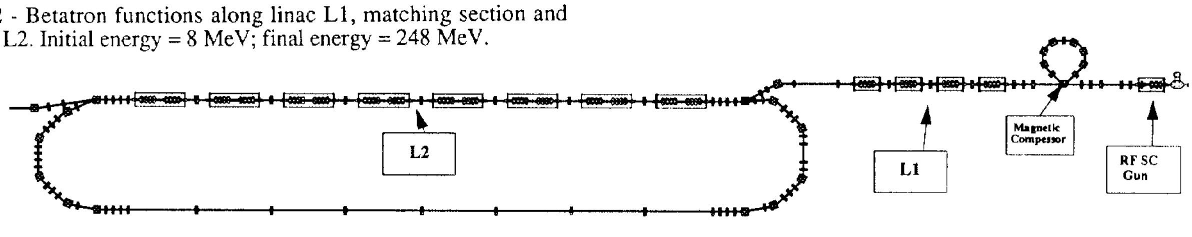

Fig.1 - Layout of the machine

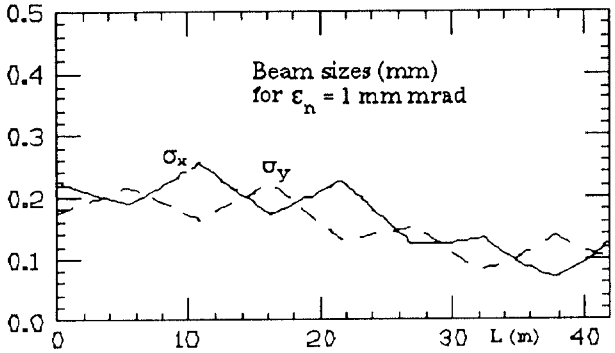

Fig.5 - Beam transverse sizes along linac L2 on the second passage for a normalized emittance of 1×10^{-6} m rad. Initial energy= 248 MeV; final energy = 440 MeV.

Recirculation lattices

The recirculation line must fulfil two basic requirements: achromaticity and isochronism. Both depend on the trajectories inside the bending magnets and are therefore driven by the arcs. We recall that, for ultrarelativistic particles, an isochronous line is also achromatic and that the condition of isochronism is fulfilled if the integral over the arc of the dispersion function divided by the curvature radius vanishes. To meet the above specification a symmetric configuration with four dipoles, each bending the beam through 45°, has been chosen. Negative dispersion is produced at the two inner dipoles, so as to compensate both the positive dispersion introduced by the two outer dipoles and that produced by the splitter. The eigenvalues of the FODO lattice configuration along L2, described above, provide the betatron function values at the output of L2; these are matched to those of the arc by a first matching section containing four quadrupoles. The quadrupoles are 0.30 m long. The highest quadrupole field gradient is G_{max} = 7 T/m. The matching conditions to be fulfilled by the other matching sections - at the other end of the first arc and at both ends of the second arc- are of course different and the sections will consequently be tuned differently.

The optical functions have been forced to be symmetric with respect to the center of the arc. Their maximum values are less than 20 m, and the maxima occur in the nondispersive region, where there is no momentum spread contribution to the beam size. In the region where the horizontal dispersion function, D_x, is non-zero the maximum value of dispersion is D_x^{max} = 0.6 m and β_x is always less than 7 m. The optical functions along the matching section and one-half arc are plotted in fig.6.

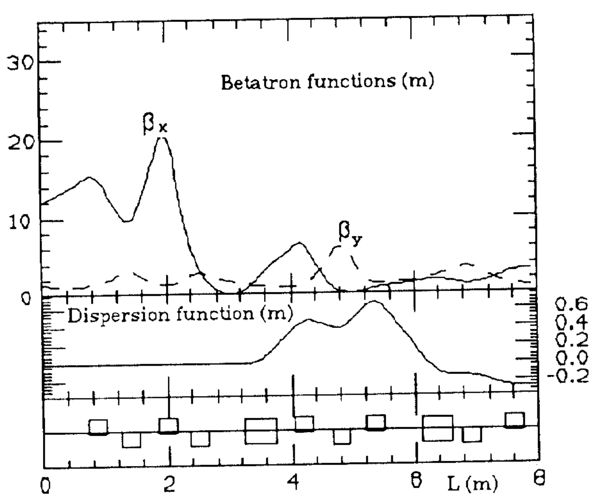

Fig.6 - Optical functions in the matching section between L2 and the arc and along half recirculating arc .

Accelerating Field and HOM in ARES Cavity

In the ARES cavity the resonant mode TM_{010} in the π configuration is used for acceleration (Fig. 7). The cells have been properly shaped in order to have the mode at the nominal frequency, with almost the same field amplitude inside each cell (field flatness of few per cent).

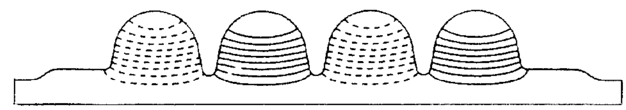

Fig. 7a - Schematic drawing of the ARES cavity showing the accelerating electric field, which is normalized to 1 MeV/m.

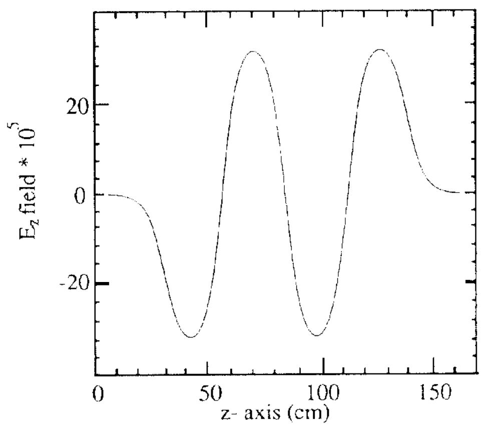

Fig. 7b - Behaviour of the accelerating electric field normalized to 1 MeV/m.

A list of the monopole modes (HOM), computed by means of the codes OSCAR2D[3] and URMEL, is presented in Table 1 together with the expected values of the R/Q parameter. The field pattern of a few TM_{0np} modes are shown in Figs.8.

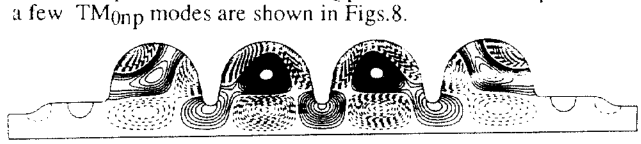

Fig. 8a - Electric field lines of the "trapped mode" TM_{032}

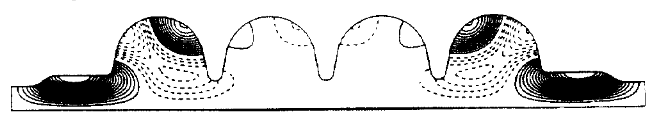

Fig. 8b - Electric field lines of the "tube mode".

Induced Wake fields

The first step in the analysis of collective phenomena is to estimate the integrated longitudinal and transverse wakes. For closed structures, both the longitudinal and the transverse impulsive wakes can be calculated as sums over the normal modes of the structure. This method is however in practice limited by the fact that an r.f. cavity is not a perfectly "closed space" so that, above the iris cut-off frequency, some analytical correction is needed. We estimated the impulsive wake potentials by applying general frequency-scaling laws to the SLAC and CEBAF wake-potentials. The approximate result has then been used to derive the bunch wakes and compare them with those calculated directly in the time domain by means of the TBCI computer code. The code computes the wakefield induced by a gaussian bunch integrated over the bunch distribution that approaches the wake Green function for very short bunches . The scaled impulsive wakes are shown in Fig.9. The bunch wakes are compared to the TBCI results in Fig.10 for various bunch lengths σ_s.

Table I - Monopole modes.

MODE	f (MHz)	R/Q (Ohm)	
TM0 - EE - 1	492.55	0.0	
TM0 - ME - 1	495.48	0.0	
TM0 - EE - 2	498.47	0.0	
TM0 - ME - 2	499.74	237.8	
TM0 - EE - 3	886.02	0.0	
TM0 - ME - 3	894.29	4.3	
TM0 - EE - 4	903.16	25.0	
TM0 - ME - 4	906.73	54.5	
TM0 - EE - 5	1040.18	0.0	
TM0 - ME - 5	1047.71	0.6	
TM0 - EE - 6	1057.60	0.1	
TM0 - ME - 6	1066.59	0.1	
TM0 - EE - 7	1239.33	1.1	'tube' mode
TM0 - ME - 7	1239.39	0.3	'tube' mode
TM0 - EE - 8	1322.45	0.2	
TM0 - ME - 8	1344.33	0.0	
TM0 - EE - 9	1368.65	0.5	
TM0 - ME - 9	1388.70	0.0	
TM0 - ME -10	1421.02	4.8	
TM0 - EE - 10	1421.86	1.9	
TM0 - EE - 11	1508.86	0.0	
TM0 - ME- 11	1522.26	0.4	
TM0 - EE - 12	1558.28	0.1	
TM0 - ME - 12	1600.60	3.8	
TM0 - EE - 13	1654.92	0.2	
TM0 - ME - 13	1660.04	0.1	
TM0 - ME -14	1792.14	21.6	
TM0 - EE - 14	1797.68	5.8	
TM0 - EE - 15	1811.70	1.5	
TM0 - ME- 15	1840.60	0.5	

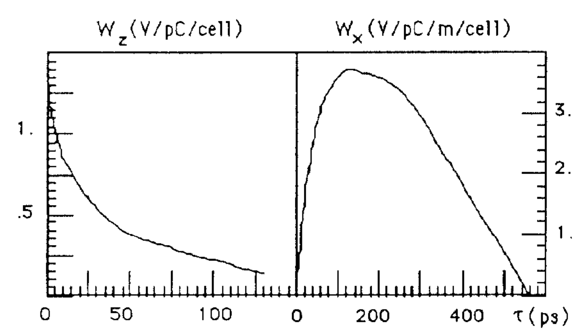

Fig.9 - Scaled impulsive wakes.

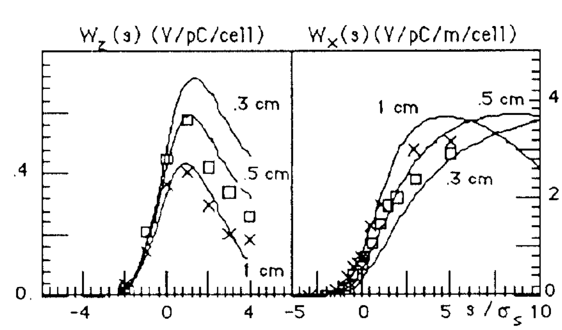

Fig.10 - The bunch wakes (TBCI : × = 1 cm, =0.5 cm) .

Table II - Dipole modes.

MODE	f (MHz)	R/Q (Ohm) at r_0 = 7 cm
1 - ME - 1	632.02	0.5
1 - EE - 1	641.26	2.3
1 - ME - 2	657.17	16.9
1 - EE - 2	677.29	14.2
1 - ME - 3	705.93	3.8
1 - EE - 3	719.19	23.5
1 - ME - 4	729.77	16.3
1 - EE - 4	735.05	1.6
1 - ME - 5	948.47	2.2
1 - EE - 5	948.53	0.0
1 - ME - 6	974.64	2.6
1 - EE - 6	977.26	0.6
1 - ME - 7	977.71	54.0
1 - EE - 7	1069.53	0.7
1 - ME - 8	1089.11	0.2
1 - EE - 8	1114.50	4.3
1 - ME - 9	1140.92	0.0
1 - EE - 9	1168.02	2.2
1 - ME -10	1168.60	2.6
1 - EE -10	1176.90	0.1
1 - ME -11	1180.00	1.7
1 - EE -11	1188.50	0.6
1 - EE -12	1275.69	0.7
1 - ME -12	1275.94	0.9
1 - ME -13	1282.53	0.0
1 - EE -13	1283.26	1.3
1 - ME -14	1328.85	1.6
1 - EE -14	1352.80	1.3
1 - ME -15	1394.34	0.1
1 - EE -15	1436.61	0.5

Single bunch Dynamics

The energy loss and energy spread for the case of the ARES Linac are given in Table III, where the design values are also reported for comparison. It must be remembered that, if required, the energy spread, because it is correlated to position, can be partly compensated by accelerating the beam off-crest, so as to make use of the slope of the external rf voltage.
Proper control of the energy spread to position correlation can also be used to produce NBS damping of the transverse motion.
In the smooth focusing approximation the emittance degradation for the nominal values is always less than 1% and is therefore negligible. The advantage of the low -frequency structure is here most evident.

Table III - ARES Linac energy loss and energy spread

Bunch Length σ_l	[mm]	3	5	10
Energy loss per cell	[keV]	.44	.38 .41*	.29 .29*
Linac total energy loss	[keV]	35.	30. 33.*	23. 23.*
Energy spread per cell	[keV]	.22	.18	.13
Linac total energy spread	[keV]	18.	14.	10.

* TBCI calculations

References

[1] S.Bartalucci, M.Bassetti, L.Palumbo, " Dynamics of a charged particle in an accelerating field", Il Nuovo Cimento, Vol. 104B, 481(1989).
[2] S.Bartalucci et al., " LISA : Beam transport and Dynamics", these proceedings.
[3] P. Fernandes, R.Parodi, " Computation of e.m. fields in TE and TM resonator and waveguides" IEEE Trans. MAG-21 (6), 2246(1985).