BEAM DYNAMICS IN A PROPOSED 350 MHZ SC LINAC FOR NUCLEAR WASTE TRANSMUTATION AND ENERGY PRODUCTION

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Abstract

A 100-1600 MeV, 25 mA, superconducting proton linac is under study by INFN for waste transmutation and energy production[1]. The linac is composed of three sections with elliptical five cell superconducting RF cavities (350 MHz) designed for synchronous β of 0.5, 0.65 and 0.85. Transverse focusing is provided by a doublet lattice. The linear beam dynamics in the sections has been studied. Due to the wide bore of the 350 MHz cavities, the ratio of the linac aperture to the rms beam radius is greater than 20 along the linac, to reduce activation by halo losses. Beam dynamic simulations with a multiparticle tracking code are in progress. The results from the linear and non linear analysis are summarized in this paper, together with a description of the proposed lattice parameters.

1 INTRODUCTION

INFN has started a two year program (TRASCO) aimed to the conceptual design and to the R&D on components of a high power proton linac for nuclear waste transmutation. The accelerator has a room temperature low energy part consisting of an ECR ion source, a RFQ up to 5 MeV and a DTL linac or more advanced type of linac up to 100 MeV. The high energy end (100-1600 MeV) is foreseen as a superconducting linac at the CERN-LEP 352.2 MHz frequency. The rationale of this choice has already been presented elsewhere[2].

The superconducting linac uses five cell elliptical cavities designed for synchronous beta of 0.5, 0.65, 0.85; the choice of three sections and their range in energy has been based on the efficiency of the cavities[2].

The transverse focusing is provided by a periodic array of quadrupole doublets, and the cavity cryostats are placed in the drift between the doublets. The cryostats accommodate 2, 3 and 4 cavities in the three sections. The length of the periods are 8.0, 11.2 and 15.3 m.

The energy gain in the cavities, at the nominal synchronous phase ϕ_s=-30 deg, is reported in Fig. 1 together with the maximum gain allowed by a peak surface field of 15 MV/m. At the nominal current of 25 mA and with 10 MeV of peak energy gain in the cavities of the third section (see Fig. 1), the maximum power of the coupler is 250 kW, a value which is in the state of the art.

A separate paper[3] at this Conference reports the design and the prototype development of the cavities.

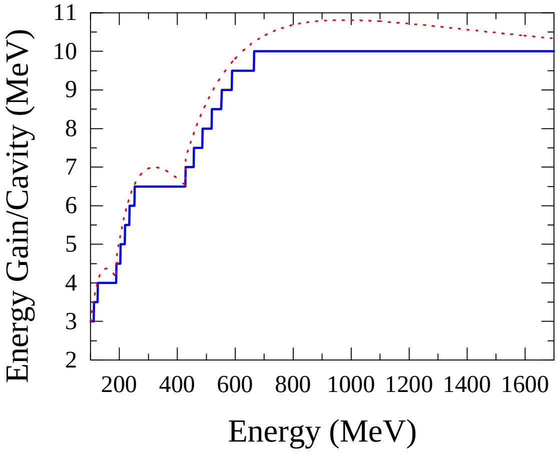

Figure 1. Maximum (dotted line) and actual energy gain per cavity along the accelerator assuming a peak surface field of 15 MV/m and a synchronous phase ϕ_s=-30 deg

2 LINEAR BEAM DYNAMICS

The linear dynamics of the linac has been investigated with the code TRACE3-D[4].

Pending the definition of the low energy part of the accelerator and the corresponding beam dynamics calculations, a transverse normalized rms emittances of 0.2 π mm mrad and longitudinal rms emittance of 0.2 π deg MeV have been assumed .

The lattice parameters have been chosen so that the zero current phase advances in the first period of each section are close to 90° (a value that also minimize the beam envelope in the quadrupole region) and the tune depression is higher than 0.5.

The quadrupoles in each section have an almost constant gradient, so that the transverse phase advance is smoothly decreasing at approximately the same rate of the longitudinal phase advance. The quadrupoles have an effective length of 0.40 m, a separation of 0.6 m and a gradient below 5 T/m, corresponding to a pole field of 0.5 T for a bore radius of 100 mm.

The matching between sections is controlled with the gradient of the doublet at the interface and the tuning of the synchronous phases of the cavities close to the interface.

The zero current phase advance per meter for each doublet cell along the linac is plotted in Fig. 2. The discontinuity at the section interface is required for the matching. The tune depression for the nominal beam current of 25 mA is approximately 0.6 (transverse) and 0.7 (longitudinal) along the whole linac.

The transverse rms beam size, as calculated by TRACE3-D, is of the order of 3 mm at the beginning of the first section and decreases steadily down to 2 mm at the end of the linac. The longitudinal rms size decreases correspondingly from 3 RF degrees to less than 1 RF degree.

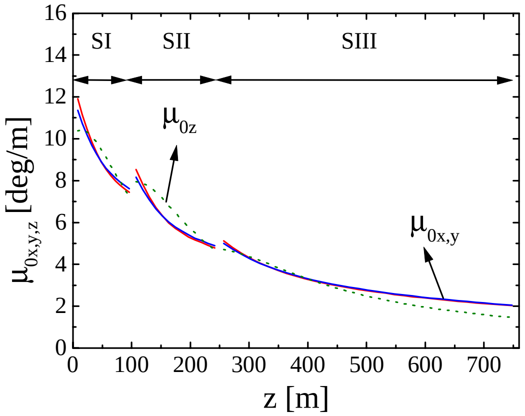

Figure 2: Zero current phase advance per meter along the linac sections.

3 MULTIPARTICLE TRACKING

3.1 The code

A multiparticle tracking code is under development in order to test the linac design, which was based on linear beam dynamics calculation. The code, written in full F90 compliance, can deal with the basic elements of the beam line, such as drift spaces, quadrupoles and multicell RF cavities. Beam tracking in the cavities is implemented with a direct integration scheme using the on-axis distribution of the accelerating electric field.

Space charge is implemented both with a direct point to point scheme between charge clouds (with a screening effect to prevent the Coulomb divergence of particle lying at close distances) and with a fast Poisson solver in the beam frame, based on charge smoothing algorithms and multigrid techniques[5] for the solution of the partial differential equation. The multigrid algorithms seem to be very appealing for their rapid convergence and for the scaling with respect to the mesh stepsize. The 3D multigrid algorithms are still in development and the simulations reported here are therefore performed with the time consuming point to point modeling, with a practical limit of few thousand particles per linac run.

Different particle loading options are possible, from uniform 1D loading in each phase space to full 6D uniform waterbag distributions. A specific algorithm for a smooth phase space loading is used[6].

3.2 Simulation results

The validation of the linac design and the exploration of the beam halo properties requires obviously a tracking code with the capability of handling particles in the range of 100000.

With the presently available point to point space charge calculation one can barely obtain indications concerning the emittance growth, since the number of particle is limited to 2000-5000. Nevertheless, it is still possible to see differences for the emittances growth related to the different lattice configurations.

The full linac (high energy part) has been simulated with 2000 particles using at the beginning of the first section a 1D distribution with the nominal rms emittances. The initial conditions and the matching parameters at the section crossing have been obtained with the code TRACE3-D.

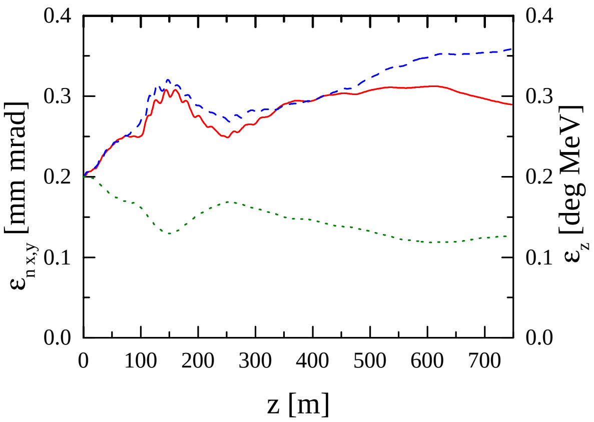

Figure 3: Normalized rms emittances along the accelerator. Solid and dashed lines: transverse plane, dotted line: longitudinal plane.

The evolution along the linac of the rms emittances is plotted in Fig. 3. The energy exchange between the transverse and the longitudinal is evident. The transverse rms emittances increase by 70%, while the longitudinal decreases by 40%. Contrary to what is reported in the literature (mostly referred to 2D simulations and smooth focusing channels), these trend are moderately sensitive to mismatch.

The 90% normalized emittances are close to the 4 ε_{rms}, which is within the expectations, while the total emittances, not reliable with this few particles resolution, is in the range 10 ε_{rms} both for the transverse and the longitudinal plane in the equipartitioned case (see section 3.4). The doubling of the rms emittances has no particular relevance by itself, while critical is the extension and the distribution of the beam halo to avoid, or at least limit, the losses inside the accelerator. The correspondence between rms emittance growth and the worsening of the halo problem is widely established in the literature.

3.3 *Emittance growth and equipartitioning*

The emittance growth observed in operating linacs and in computation can be explained[7] in terms of the general principle of equipartition of the energy in the beam frame. No emittance change should then be observed if, in the beam frame, each degree of freedom has the same energy at injection as well as during the acceleration process.

We note that the equipartition criteria is well defined only for continuous focusing channels, while for periodic alternating gradient structures it can be defined qualitatively only in term of the smooth approximation. The energy ratio transverse/longitudinal can be given as a function of the normalized emittances and of phase advance per period as $\varepsilon_t \mu_t / \varepsilon_l \mu_l$.

The actual design does not satisfy the beam equipartitioning criteria. In the first section, where there is a transverse emittance increase of 30 %, the equipartitioning ratio is of the order of 0.3. It is not clear which are the allowed limits for this ratio, since it is difficult to design a linac exactly satisfying this criterion.

The ESS linac[8] has ratio of transverse/longitudinal energy going from 0.5 at injection up to 2.5 at the linac end without increase of the rms emittances.

Similar values have been used in the APT linac design at Los Alamos; a comparison with an equipartitioned case is reported in Ref. [9].

3.4 *Control of the emittance growth*

Using as a guideline the equipartition criteria two alternatives have been explored to avoid emittance growth (and to control the beam halo).

1. A reduction of the period length in each section. The sections should contain respectively 1, 2, 2 cavities. This gives a big decrease in the longitudinal phase advance per period. This is not a desirable solution because of the increase of the linac length.

2. An increase of the transverse normalized rms emittance by a factor 2 to 0.4 π mm mrad. The beam size increases approximately by 50%, still maintaining the ratio of the beam pipe to the rms beam size of the order of 20. There is also an increase of the transverse phase advance because of the reduced space charge effects. Problems may arise in the DTL section.

With this emittance change the equipartition ratio has been increased to approximately 0.8 in the first section.

The rms emittances evolution along the linac are plotted in Fig. 4. The variation are contained within 5%; the transverse increase in the second section (z=100-250 m) is not easily explained, since there the equipartitioning ratio is well above 0.7.

The corresponding rms beam sizes are plotted in Fig. 5 The same gradients as the nominal case have been used for the quadrupoles, with no attempt to optimize the matching between the sections.

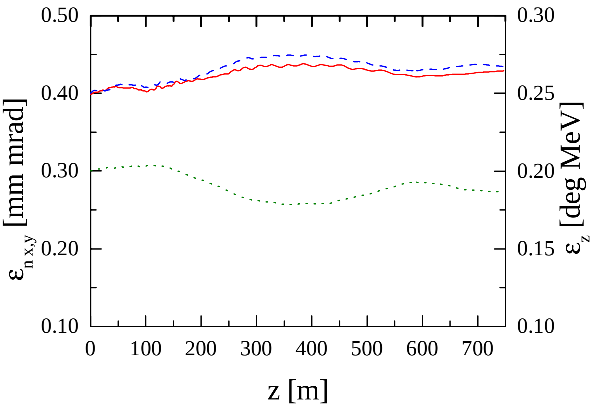

Figure 4: Normalized rms emittances along the linac. Solid and dashed lines: transverse, dotted: longitudinal.

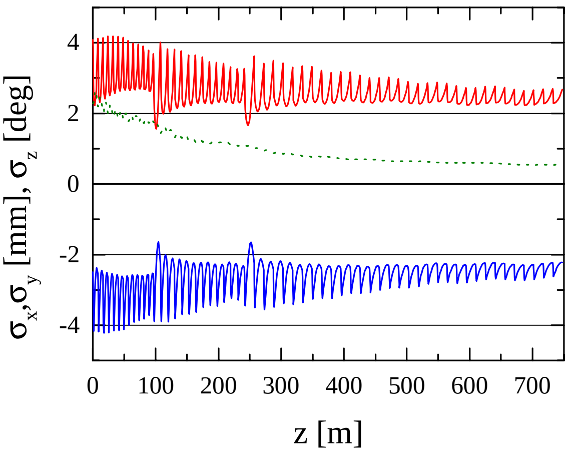

Figure 5: rms beam sizes along the linac. Upper: x, lower: y, dotted: phase.

4 CONCLUSIONS

The preliminary beam dynamics simulations of the linac have shown no major design faults. The emittance growth can be handled using as a guideline the equipartitioning criteria and possible schemes are under investigation. A revision of the linac design will be undertaken when tracking simulations with a greater resolution will be available.

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