DESIGN CONSIDERATIONS OF THE ESS COUPLED CAVITY LINAC

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Abstract

Part of the 5 MW European Spallation Source (ESS) project is a 700 MHz coupled cavity linac (CCL). It accelerates H^-– ions from 150 MeV up to 1.334 GeV. The peak current is 100 mA and the average current is 3.75 mA. The duty cycle is 6.2 %. First design considerations result in an accelerating gradient E_0T of about 2.4 MV/m. The value is close to the cost minimum including ten years of operation. A modular design is foreseen using 3 MW klystrons feeding two tanks. For having a smooth beam radius the focusing is done by doublets between the tanks. Multiparticle calculations show that the beam has to be equipartitioned between transverse and longitudinal direction to get no rms emittance growth.

Layout of ESS and linac

The need for a future pulsed neutron source in Europe has led users and machine designers to propose the following parameters for the ESS[1,2]:

- An average beam power of 5 MW
- A beam pulse at the target less than 3 μsec long
- A repetition rate of 50 Hz
- Two target stations, one operating at 50 MHz, 5 MW and a second one at 10 Hz, 1 MW

To achieve these parameters a combination of a linear accelerator and two storage rings is proposed. The linear accelerator accelerates H^-– ions in pulses of 1.2 msec length up to 1.334 GeV. With a 50 Hz repetition rate the beam is injected into two accumulator rings[3]. This system offers a great flexibility. It can give an average beam of 5 MW for 1 μsec long pulses by using both compressor rings, or it gives 2.5 MW beam power for 0.4 μsec long pulses using one compressor ring. In addition the linac can be operated in "dual pulse mode". Every fifth pulse can be unchopped and lengthened up to 2 msec and guided directly to an additional 10 Hz target with 2.7 MW beam power. The four other pulses go via the compressor rings to the 50 Hz target delivering 4 MW. This mode increases the duty cycle from 6.2 to 7 %.

The ESS linear accelerator design is dominated mainly by two conditions. Particles loss along the linac has to be in the order of $10^{-7}...10^{-6}$/m and a low loss injection and extraction scheme of the compressor rings in order to allow hands on maintenance. For the particle loss no method of detailed calculation exists. Qualitative arguments have to be used: along the linac including low and high energy transfer lines all known sources causing transverse and longitudinal emittance growth have to be avoided. In general the linac design should be conservative to provide enough safety margins. To have a low loss injection the linac pulse has to be chopped with an efficiency of 60 %, and the number of injected turns per ring should be not greater than 1000 which limits the beam pulse length to about 1.2 msec. This results in a peak current of 100 mA, or if the chopping efficiency is taken into account, in an effective pulse current of 60 mA. In addition the energy spread has to be less than ±1 MeV. The halo containment above this energy should be not more than 10^{-4} particles. This requires a small emittance and a bunch rotation system between linac and accumulator rings.

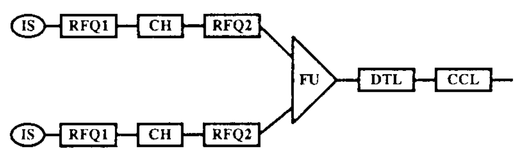

Fig. 1 ESS linac layout: IS: ion source, CH: chopper, FU: funneling

The layout of the linac is shown in Fig. 1. To achieve 100 mA peak current and at the same time small emittances funneling is proposed with two front end legs. Each leg has a 70 mA, 70 kV, 10 % d.c. H^-– ion source followed by a 175 MHz, 2 MeV RFQ. After the RFQ the beam passes a line with a fast chopper. The chopper provides sharp edges of the pulses reducing the number of partly filled buckets. A second RFQ accelerates the beam up to 5 – 7 MeV. Its frequency is at 175 or at 350 MHz. The two beams are funneled together after the second RFQ. The chopping and the funneling line contain bunchers to maintain the longitudinal emittance. In the following 350 MHz drift tube linac (DTL) the particles are accelerated up to 150 MeV. Each front end leg will deliver 50 mA. The beam current in the DTL is then 100 mA. The DTL design will be conservative having the peak surface field kept below the Kilpatrick limit of 18 MV/m. After the DTL particles are accelerated up to 1.334 GeV by a coupled cavity linac (CCL).

CCL parameter and design

For the high β linac normal conducting (nc) and superconducting (sc) structures are under discussion. Here we restrict ourselves to nc cavities. A good choice for a nc structure is a 700 MHz side coupled cavity. 805 MHz side coupled linacs operate successfully and reliable at Los Alamos and Fermilab. The disk and washer (DAW) structure is also a possible candidate. In TABLE 1 the CCL parameters are listed.

Minimization of costs and losses are the two major design criteria of the CCL. As a result of minimizing costs E_0T = 2.4 MV/m has been chosen. Costs include structure, rf and ten years of operation. Buildings are also included but without extensive shielding. Values for shunt impedance and transit time factors were fitted to data calculated for the LAMPF linac in Los Alamos [4]. These theoretical shunt impedance values were reduced by 20 % taking into account additional rf losses in real cavities. Therefore the realistic shunt impedance changes along the linac from 29 up to 41 MΩ/m. The transit time factor stays more or less constant at 0.81. The beam hole diameter of the cavities is about 4.4 cm. It is assumed that the klystron delivers 3 MW peak power and up to 300 kW average power. One klystron will feed two tanks coupled by a bridge coupler. The choice of one klystron feeding one tank only with 3 MW (this means no bridge coupler) is not possible. Tanks would get too long and therefore the phase slip would get too large and transverse focusing more difficult. Even with the actual choice (one klystron / two tanks) the phase slip is around ±15 deg at linac injection. We splitted the linac into two sections where the first section goes up to 500 MeV. In this section klystrons run only at 2.5 MW peak power. It gives shorter tanks, e.g. 3.6 m at 150 MeV, and a phase slip of ± 10 deg. Above 500 MeV in section 2 the klystron power is at its normal value of 3 MW. At higher energies the tanks can be longer because the phase slip decreases with increasing energy. The synchronous phase in section 1 is equal to -30 deg and equal to -25 deg in section 2.

TABLE 1
CCL parameter

Input energy	150 MeV
Output energy	1334 MeV
Frequency	700 MHz
Repetition rate	50 Hz
duty cycle	6.2 %
Effective pulse current	60 mA
Average current	3.75 mA
Acc. grad. E_0T	2.4 MV/m
Synchronuous phase	-30/-25 deg
Shunt impedance	29...41 MΩ/m
Transit time factor	0.81
Peak power beam	70 MW
Peak power structure	90 MW
Average CCL power	10 MW
Peak power per klystron	3 MW
Number of klystrons	57
Number of tanks	114
Tank length	3.6...5.5 m
Average cell number per tank	30
Focusing	doublets
Quadrupole gradient	21...15 T/m
CCL length	620 m
Bore hole diameter	4.4 cm

The transverse focusing of the beam is done by doublets. The two quads are 15 cm long each and separated by a 10 cm long drift space. The magnetic gradient decreases from 21 T/m at 150 MeV down to 15 T/m at 1.3 GeV. Linear calculations including full space charge showed for the doublet in comparison to singlets: the absolute beam envelope maximum is less and the absolute beam envelope minimum is larger. With respect to particle losses doublets have been chosen. Before and after the doublet drift spaces are foreseen to house diagnostics and beam steering elements. The total interspace length should be $3\beta\lambda/2$ or $5\beta\lambda/2$. β is the ratio between the velocity of the synchronous particle in the intertank space and the speed of light and λ is the rf - wavelength. The intertank space should not be less than 60 cm. An option which has not been considered in detail yet would be to split the power of one klystron between four tanks. This would give shorter tanks, smaller phase slip and more intertank space for additional diagnostics, beam steerers and also focusing by singlets becomes possible.

Beam dynamics in the ESS linac

Due to the frequency of 700 MHz in the CCL which is twice the frequency of the DTL only every second bucket in the CCL is occupied by a bunch. The beam current to be handled therefore increases to an effective peak current of 200 mA. For the normalized rms emittances the following values are assumed: $E_{tn}^{rms} = 0.6\ \pi$ mm mrad and $E_{ln}^{rms} = 1.2\ \pi$ deg MeV. The emittances are consistent with the expected output emittances of RFQ1 including some growth in the chopping and funneling line. With given current and emittances the quadrupole gradients have to be set such that resonances and other sources of emittance growth can be avoided. The calculation is done in a linear way. A problem was that for choosing a constant transverse tune σ_t like 30, 45 or 60 deg per period the beam gets longitudinal unstable at some medium energy. One possibility to overcome this problem is to relax the longitudinal space charge force by decreasing the transverse tune at higher energies. A good solution is changing the tune as given by $\sigma_t = 60^0\ (\gamma_0/\gamma)^2$. γ is the relativistic factor and γ_0 its value at 150 MeV. Fig. 2 shows the variation of the transverse and longitudinal tune as a function of energy.

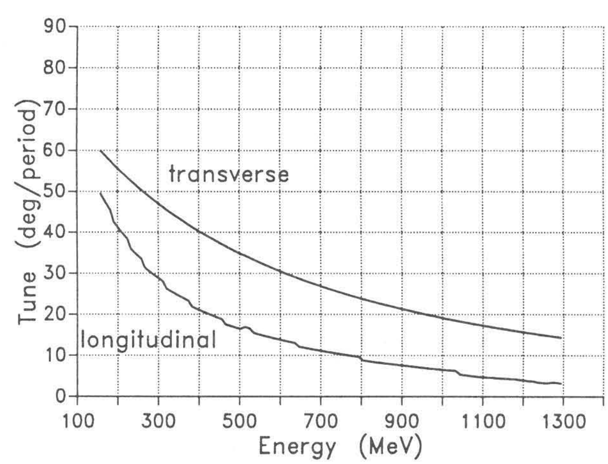

Fig. 2 Transverse and longitudinal tune as a function of energy

For zero current the transverse tune at 150 MeV increases up to 81 deg giving a tune depression of 0.74. The longitudinal tune depression is equal to 0.71. The values indicate that the CCL has to handle a high current but the machine is not at its ultimate limit. In TABLE 2 the beam parameters in the CCL are listed at 150 MeV.

TABLE 2
Beam parameters at injection into the CCL at 150 MeV

Effective peak current	200 mA
Transverse rms emittance	0.6 π mm mrad
Longitudinal rms emittance	1.2 π deg MeV
Transverse tune	60 deg
Transverse tune depression	0.74
Longitudianl tune	49 deg
Longitudianl tune depression	0.71

The analysis of the rms emittance growth was done by multiparticle calculations. To have a flexible code for our purposes we have developed a new program. It calculates the space charge in the middle of every drift space, quadrupole and accelerating cell. Space charge is taken into account by summing up the Coulomb forces between the macroparticles. The number of macroparticles simulated have been varied and it turns out that with more than 1000 macroparticles the rms values do not change significantly. As a result Fig. 3 shows the rms emittance of 2000 macroparticles for the data in TABLE 2 as a function of energy. The initial phase space distribution is a 4–dimensional waterbag in the transverse and a 2–dimensional waterbag in the longitudinal phase space. No significant rms emittance increase is seen. This is because the beam is close to equipartition. The equipartition ratio $E_t\sigma_t/E_l\sigma_l$ is about 0.65 at injection and increases to 1 around 260 MeV. If the initial longitudinal rms emittance is doubled simulation runs show a significant transverse rms emittance increase. Longitudinal energy is pumped into the transverse direction. This leads to the conclusion that the longitudinal emittance has to be handled very carefully from the first RFQ onwards. Uncontrolled longitudinal emittance growth can be critical.

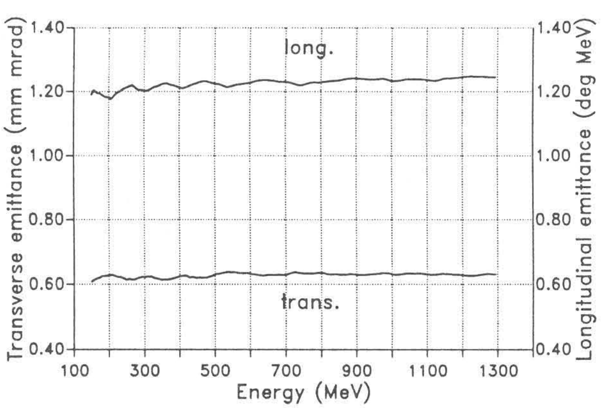

Fig. 3 Normalized transverse and longitudinal rms emittances in the CCL

The variation of the transverse tune proportional to $1/\gamma^2$ also causes a growth of the rms beam radius. In Fig. 4 the beam radius profile for the x and y direction is shown. The rms radii are plotted at the end of each tank. The growth is acceptable as long as the rms values stay below 3 mm. At 1.3 GeV the beam radius is critical due Lorentz-stripping of the H^- – ions in the focusing quadrupoles. In order to allow hands on maintenance beam core particles should have a radius less than 1.2 cm for a magnetic gradient B' = 15 T/m. The proposed design is insensitive against matching and quadrupole gradient errors. This is demonstrated in Fig. 4, where section 2 (above 500 MeV) starts with a mismatch. No rms emittance increase is recognized.

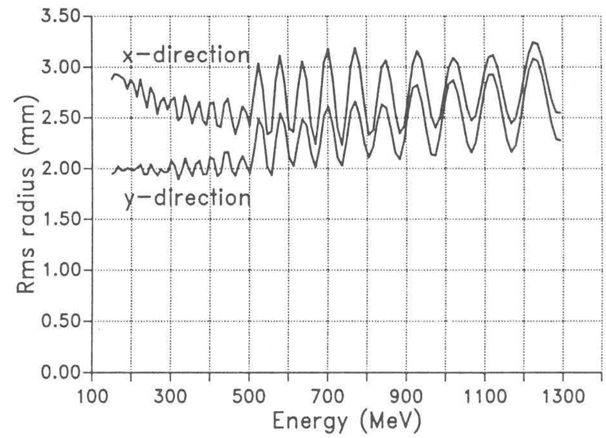

Fig. 4 Rms beam radius for both transverse directions in the CCL. Data are plotted at the end of each tank.

Summary

We presented a layout and the beam dynamics of the 700 MHz, 100 mA peak current, 1.3 GeV coupled cavity linac of the European Spallation Source. The major design goals are minimization of costs and losses. By minimizing costs of structure and rf including ten years of operation an accelerating gradient E_0T = 2.4 MV/m results. The structure is not determined yet but because of its reliability side coupled cavities would be a good choice. As rf sources 3 MW peak and 300 kW average power klystrons are foreseen. With respect to particle loss machine and beam parameters have to be fixed such that sources of rms emittance growth are avoided. As seen in multiparticle calculations no rms emittance growth takes place. Transverse focusing is provided by doublets. Doublets are favored above singlets to have a more round beam and a smaller beam diameter.

References

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