BEAM DYNAMICS IN THE 1.3 GeV HIGH INTENSITY ESS COUPLED CAVITY LINAC

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The 700 MHz coupled cavity linac (CCL) of the European Spallation source (ESS) accelerates H^- – ions up to 1.334 GeV. The bunch current is 214 mA and the average current 3.84 mA. Four tanks are fed by one 4 MW klystron. The phase slip of 4° at injection is not critical. After every second tank a doublet is installed for transverse focusing providing a 'round' beam. The other intertank sections are used for beam diagnostic elements and steering. To find the smallest injection energy rms and total emittances are studied by multiparticle calculations and by varying the injection energy between 70 and 150 MeV. In addition the influence of field and phase errors is considered. For the low loss injection into the following compressor rings the problem of partly filled bunches is examined.

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 5.1 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, 5.1 MW and a second one at 10 Hz, 1 MW

These parameters will be achieved by a combination of a linear accelerator and two storage rings. 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].

The layout of the linac is shown in Fig. 1. To achieve 107 mA peak current and at the same time small emittances, funneling is proposed with two front end legs. Each leg will deliver 54 mA.

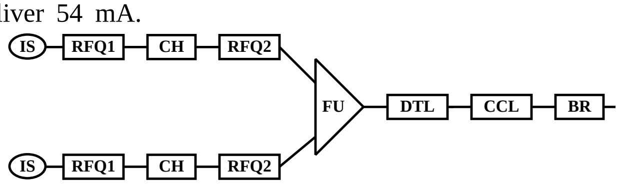

Fig. 1 ESS linac layout: IS: ion source, CH: chopper, FU: funneling, BR: bunch rotator

CCL PARAMETER AND DESIGN

Basis of the 700 MHz CCL design are the 805 MHz side coupled linacs operating successful and reliable at Los Alamos and Fermilab. Table 1 lists the main parameters of the CCL.

TABLE 1
CCL parameter

Input energy	70	MeV
Output energy	1334	MeV
Frequency	700	MHz
Repetition rate	50	Hz
duty cycle	6.0	%
Bunch current	214	mA
Effective pulse current	64	mA
Average current	3.84	mA
Acc. grad. E_0T	2.8	MV/m
Synchronous phase	–25	deg
Shunt impedance	29...41	MΩ/m
Transit time factor	0.83	
Peak power beam	81	MW
Peak power structure	113	MW
Average CCL power	12	MW
Eff. peak power per klystron	3	MW
Number of klystrons	66	
Number of tanks	264	
Tank length	1.3...2	m
Cell number per tank	16...10	
Focusing	doublets	
Quadrupole gradient	25...15	T/m
CCL length	≤663	m
Bore hole diameter	4.4	cm

The design of the CCL is ruled mainly by the minimization of costs and losses. Costs are minimized by choosing an accelerating gradient E_0T = 2.8 MV/m. These costs include structure, rf, ten years of operation and buildings without extensive shielding [4]. Concerning losses one has to be aware of 'matching' losses in the transverse and longitudinal direction resulting from the change of the transverse focusing period and the accelerating gradient between the 350 MHz DTL and the 700 MHz CCL. The matching losses occur mainly after injection. Therefore the input energy of the CCL has to be low as possible, here 70 MeV, to be far below the neutron production threshold of about 120 MeV.

As power sources 4 MW multiple beam klystrons can be chosen [6]. 3 MW are for beam and structure and 1 MW will be foreseen as control power for stabilizing the transient behaviour. The tank length is determined by a required peak power of 0.75 MW for the chopped pulse mode. One klystron feeds four tanks coupled by three bridge couplers. The tank length varies between 1.27 m and 1.95 m and has cells of constant length. The shunt impedance values have been calculated with SUPERFISH [5]. The maximum phase slip is 4° in the first tank. Another possibility is to use conventional 2 MW klystrons feeding two tanks only.

Transverse focusing is provided by doublets located after every second tank in $5\beta\lambda/2$ long intertank sections. Doublets are favoured over singlets giving a more round beam with smaller average diameter and beam envelope oscillations. Diagnostic equipment and steering elements are placed in short intertank sections. The length of those is $3\beta\lambda/2$. The klystron power will be coupled into bridge couplers at long intertank sections. The increase of the intertank sections with β allows to install scrapers at the high β end and the use of less compact doublets which can be supplied by stable dc power supplies. For this layout the total length of the CCL is 663 m.

Shortening the linac is possible for choosing a less flexible layout. By skipping the short diagnostic intertank sections the tank length will be doubled. To get reasonable phase slip the length of cells has to be changed within the first tanks. Diagnostic and steering has to placed in the focusing sections. This reduces the CCL length by about 60 m.

BEAM DYNAMICS IN THE CCL LINAC

Due to the frequency of 700 MHz which is twice the frequency of the DTL a bunch current of 214 mA has to be accelerated by the CCL. At input the normalized transverse rms emittance is 0.6 π mm mrad and the longitudinal rms emittance is 1.2 π ^{o} MeV. Following the line of minimizing losses the tunes have to be set in a way avoiding beam resonances and other sources of emittance growth.

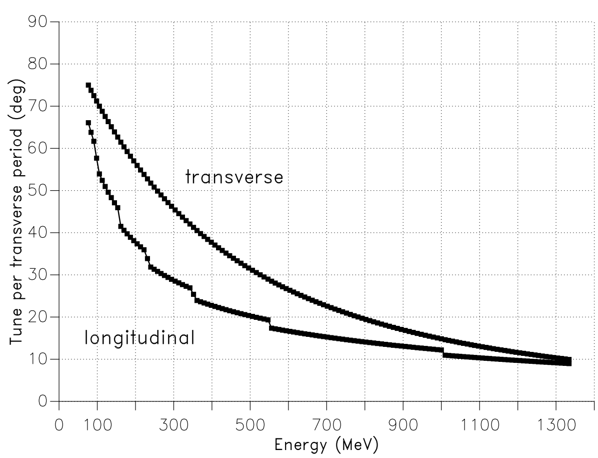

Fig. 2 Transverse and longitudinal tune as a function of energy

Several designs with varying injection energies between 70 and 150 MeV have been set up and tested by multiparticle calculation. For setting up the design we had to handle several problems. First, a constant transverse tune is not possible along the CCL. Due to a decreasing beam radius in case of a constant tune space charge increases at higher energies and the beam becomes unstable longitudinally. We solve the problem by decreasing the transverse tune σ_t with β according to$\sigma_t = \sigma_{t0}(\gamma_0/\gamma)^{-2.5}$. γ is the relativistic factor and γ_0, σ_{to} are the values at input energy. Second, to avoid energy exchange between transverse and longitudinal direction the beam has to be equipartitioned at injection. With the given emittances the transverse tune σ_{to} at input has to large but less than 90^{o} per transverse focusing period. The large tune has a useful side effect of a fast betatron oscillation which favors a loss of halo particles as soon as possible after injection.

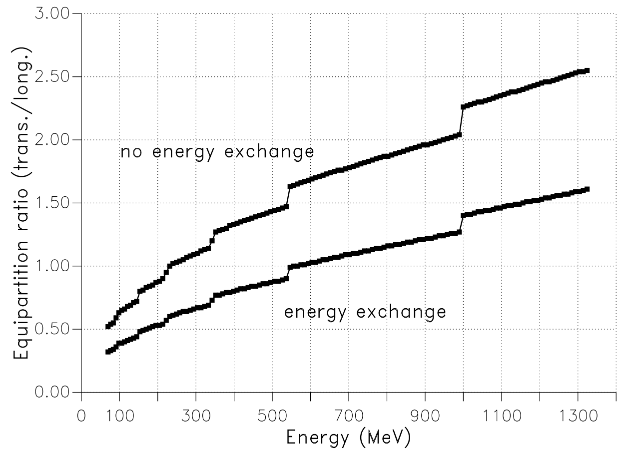

Fig. 3 Ratio of transverse to longitudinal energy (equipartition ratio)

In all cases the growth of normalized rms emittances is less than 10 % transversely and longitudinally. We finally have chosen 70 MeV as an appropriate input energy of the CCL. The transverse tune at injection was set to 75^{o}. The energy dependence of the tunes is shown in Fig. 2. The tune depressions are moderate and stay between 0.7 and 0.8 along the CCL for the transverse and longitudinal direction. The ratio of transverse to longitudinal energy (equipartition ratio) $\mathbf{E_t\sigma_t/E_l\sigma_l}$ is shown in Fig. 3. We recognized that for having no energy exchange the ratio has to be larger than 0.5 at injection. No exchange of rms emittances is seen at higher energies even if the ratio increases up to 2.5 corresponding to a nonequipartitioned beam. As an counterexample we present a beam with a ratio of 0.3 at injection, shown in Fig. 3. An energy exchange is seen from the oscillations of the rms emittances plotted in Fig. 4.

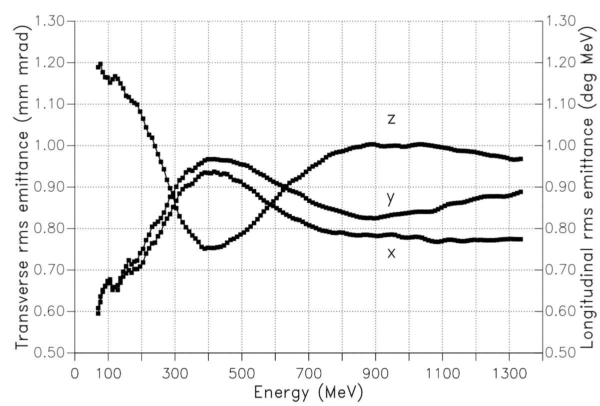

Fig. 4 Normalized transverse (x and y) and longitudinal (z) rms emittances for an nonequipartitioned beam at injection

For the total emittance the input distribution of the multiparticle calculation is important. We have chosen a 4–d waterbag transversely and a 2–d waterbag longitudinally. As a result for the equipartitioned case the total emittance increases by a factor 2.5 in all three planes. In the nonequipartitioned case we have a larger growth factor of about 3.

Concerning transverse and longitudinal acceptance for the full current we have the following data. The average beam radius is 3 mm while the bore hole radius is 22 mm. This gives a factor 7 between rms radius and aperture and a factor 50 between rms emittance and acceptance. Longitudinally the situation is somewhat different. Due to phase damping the rms phase width decreases from 6^o down to 2^o and the rms energy spread increases from 0.2 MeV up to 0.6 MeV. The phase acceptance is about $\pm 25^o$ and constant along the CCL. The energy acceptance increases from about 0.5 MeV up to 6 MeV. The resulting acceptance increases from 12.5 π ^{o} MeV to 160 π ^{o}MeV giving a factor 10 between the longitudinal rms emittance and the acceptance at injection and a factor 130 at the linac end.

ERRORS AND PARTLY FILLED BUNCHES

We also studied field and phase errors. For each tank a field error ≤1% and a phase error $\leq 1^o$ is assumed. The errors are distributed randomly within the limits. This type of errors will effect mainly the motion of the bunch center longitudinally. Fig. 5 shows the oscillation of the bunch center around the synchronous energy. At the end of the CCL the amplitude has grown up to 0.6 MeV which is of same order as the rms energy spread. If no errors are present the amplitude is by a factor 10 smaller. As the rms energy spread is reduced by a factor 3 in the transfer line after the CCL, errors of 1% for field and 1^o for phase are the upper limit. Rms values of emittances, radii, phase width and energy spread do not differ much if errors are present or not. An effect can be seen for the total emittances. Here the growth factor is 3.5, larger as if no errors are present.

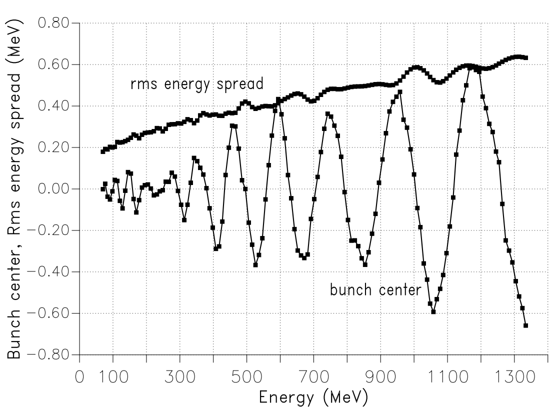

Fig. 5 Energy of the bunch center in the longitudinal phase space and rms energy spread

For the injection into the compressor rings the beam pulse has to be chopped at around 2 MeV. During switching the chopper can create bunches carrying less current than the design value. Those partly filled bunches cause problems in the transfer line between the CCL and the compressor rings [7]. If a bunch carries not the full current the bunch is mismatched mainly in transverse direction. However, because the current is less the average beam radius is somewhat reduced. We simulated two cases, one with half the design current and another one with 1% of the design current. As a result we see larger oscillations of the rms radii but the maxima of the rms radii decreases with the current. Also, we see no effect at the emittances. Unfortunately the partly filled bunches pass the CCL and cause problems in the following transfer line. Therefore, the low energy chopping system has to avoid partly filled bunches.

SUMMARY

We studied the beam dynamics of the 700 MHz, 214 mA bunch current, 1.334 GeV coupled cavity linac of the European Spallation Source. The major goal is the minimization of losses. We approach this goal by avoiding all known sources of emittance growth. For the CCL mainly two conditions have to fulfilled:

- The beam has to be equipartitioned at injection to avoid exchange of energy
- The transverse tune has to be decreased with increasing energy to avoid longitudinal instability

As a consequence of those conditions the increase of the rms emittance is less than 10%. Total emittances grow by a factor 2.5. Field and phase errors cause mainly an oscillation of the longitudinal bunch center. The errors should not be larger than 1% for the accelerating field and 1^o in phase. The low energy chopping system has to avoid partly filled bunches, because those bunches pass the CCL and cause problems in the transfer line to the compressor rings.

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