# DESIGN CONSIDERATIONS FOR A SUPERCONDUCTING LINAC AS AN OPTION FOR THE ESS

W.F. Bräutigam, S.A. Martin, G. Schug, E.N. Zaplatine, FZJ Juelich; P.F. Meads, Oakland;
Y.V. Senichev,University Aarhus

*Abstract*

An approach for a superconducting high-current proton linac for the ESS has been discussed as an option in the "Proposal for a Next Generation Neutron Source for Europe- the European Spallation Source (ESS)"[1,2]. The following work studies the technical and economic conditions for a superconducting linac at the high-energy end of the proposed accelerator system. The use of superconducting elliptical cavities for the acceleration of high-energetic particles $\beta = v/c \approx 1$ is certainly state of the art. This is documented by many activities (TJNAF, TESLA, LEP, LHC, and KEK). A design study for the cavities is described in another paper on this conference[5]. For low energy particles (β<<1) quarter wave type cavities and spoke-type cavities have been discussed. The main motivation for this study is the expectation of significant cost reduction in terms of operational and possibly investment cost.

## 1 BASIC PARAMETERS

The basic parameters of the system are given in tables 1,2,3.

Table 1: Basic data of the superconducting ESS linac

| | | |
|---|---|---|
| Maximum energy | 1334 | MeV |
| maximum β=v/c | 0.91 | |
| injection energy | 70 | MeV |
| injection β | 0.4 | |
| average current | 3.75 | mA |
| peak current pulse average | 63 | mA |
| repetition rate | 50 | Hz |
| pulse length | 1.2 | ms |
| duty factor | 6 | % |

The high energy linac will transport the beam from 70 MeV up to 1334 MeV. A current of 3.75 mA is necessary for the 5 MW beam power. The pulse length of 1.2 ms is required by the filling mechanism for the 2 accumulator rings. The macro time structure of the beam is 1.2 ms out of 20 ms, result in a duty factor of 6 %. The micro time structure inside the pulse is 360 ns beam-on and 240 ns beam-off. The accumulator uses the beam-off-time for maintaining a beam free section in the circulating beam. The $2{*}10^9$ particles per bunch are not too critical for the high energy linac. The total number of particles per pulse is $4.7{*}10^{14}$.

Table 2: Pulse micro structure

| | | |
|---|---|---|
| revolution frequency accumulator | 1.67 | MHz |
| revolution time accumulator | 0.6 | µs |
| chopping beam-on time | 360 | ns |
| chopping beam-off time | 240 | ns |
| intensity | | |
| particles per pulse | $4.7\ 10^{14}$ | |
| particles per RF bunch | $2\ 10^{9}$ | |

## 2 ENERGY GAIN PER CAVITY

The energy gain in cavity is usually given by $\Delta W = eE_0 T \cdot l \cdot \cos(\phi)$. Here, T is the transit time-factor and l the length of the cavity. $E_0 T = E_{acc}$ is the accelerating field and $\phi$ is the phase distance of the synchronous particle to the crest at the centre of the cavity. The matched length of one cavity cell is given by $\Lambda = \beta_\Lambda \cdot \lambda / 2$ where $\beta_\Lambda = \beta = v/c$ the velocity factor of the synchronous particle. The cell transit-time factor is given by

$$T_\Lambda = \begin{cases} \dfrac{\pi}{2\cdot\left(1+\dfrac{2\Lambda}{\beta\cdot\lambda}\right)} & \text{for } \beta \approx \beta_\Lambda (\leq 3\%) \\[2ex] \cos\left(\pi\cdot\dfrac{\Lambda}{\beta\cdot\lambda}\right)\cdot\dfrac{1}{1-\left(\dfrac{2\Lambda}{\beta\cdot\lambda}\right)^2} & \beta \neq \beta_\Lambda \end{cases}$$

These expressions neglect the changes of beam velocities within a cell. Therefore, the lower formula is in accordance with the theory of Wangler [3].We have set up an approximate relation in order to give the validity range of the phase $\phi$. The relative $T_\Lambda$ error holds less than

$$0.5\%\ (1.5\%) \text{ for } |\phi| < 76^\circ\ (85^\circ).$$

This relation is valid up to the maximally occurring values of velocity mismatch (0.05) and the difference of the beam velocity factors within a cell (0.02).
The energy gain of an N-cell cavity results as addition of gains of N single cells. Thereby, particular synchronous phases of each cell have successively been calculated. This numerical method makes the base of future longitudinal particle tracking of the high-energy part of the linac.

Table 3: Radiofrequency system

| | | |
|---|---|---|
| frequency | 700 | MHz |
| RF wave length | 0.428 | m |
| data for a β=0.75 cavity: | | |
| length of a cell Λ | 0.182 | m |
| length of a 5-cell cavity | 0.91 | m |
| maximum surface electric field $E_{peak}$ | 25 | MV/m |
| accelerating field $E_{acc}$ | 10 | MeV/m |
| transit time factor per cell $T_\Lambda$ | 0.79 | |
| maximum tension amplitude per cell | 2 | MV |
| phase for acceleration in cell #3 | -20 | degree |

The β-dependence of the energy gain of an N-cell cavity can be manifested using Wangler's formalism [3]. Here, the beam velocity along the N cells is set to be constant. The cavity transit-time factor T can then be factorised: $T = T_\Lambda \cdot T_S$.Where the synchronism factor is given by

$$T_S\left(N,\frac{\beta}{\beta_\Lambda}\right)=\begin{cases}(-1)^{\frac{N-1}{2}}\cdot\dfrac{\cos\left(\dfrac{N\pi\beta_\Lambda}{2\beta}\right)}{N\cdot\cos\left(\dfrac{\pi\beta_\Lambda}{2\beta}\right)}, & \text{N - odd}\\ (-1)^{\frac{N}{2}+1}\cdot\dfrac{\sin\left(\dfrac{N\pi\beta_\Lambda}{2\beta}\right)}{N\cdot\cos\left(\dfrac{\pi\beta_\Lambda}{2\beta}\right)}, & \text{N - even}\end{cases}$$

where β is the centre velocity factor being constant over N cells and $\beta_\Lambda$ is the cavity geometric velocity

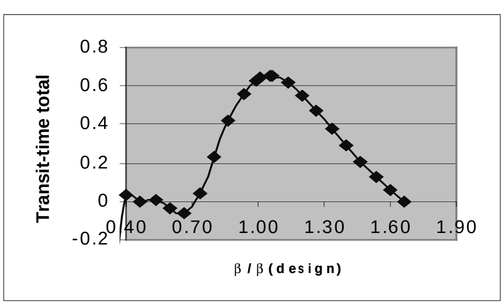


Figure 1: Transit-time factor for a 5-cell cavity vs. the velocity ratio $\beta/\beta_\Lambda$ including β change from cell to cell

factor. The number of cells per cavity has been chosen to be N=5. The transit-time factor for such a 5-cell cavity is shown in the figure 1.

The maximum value occurs at the design velocity factor $\beta_D$, which is a little larger than the geometric velocity $\beta_\Lambda$.

## 3 $\beta$-GROUPING

The cell number N=5 have been chosen for ESS because of the smaller influence of the end cells compared to N=4. We have slightly rearranged the high energy linac part by fixing the maximal surface electric field to 25 MV/m. The ratio Epeak/Eacc has been calculated in [4].

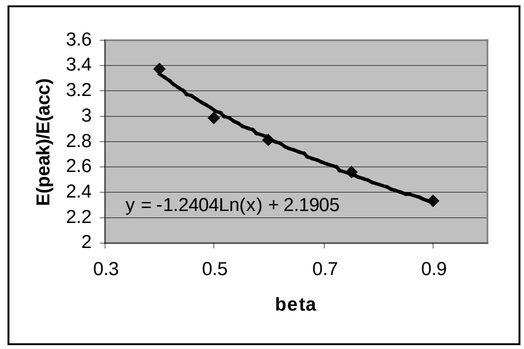


Figure 2: Ratio $E_{peak}/E_{acc}$ as it is calculated by the MAFIA program.

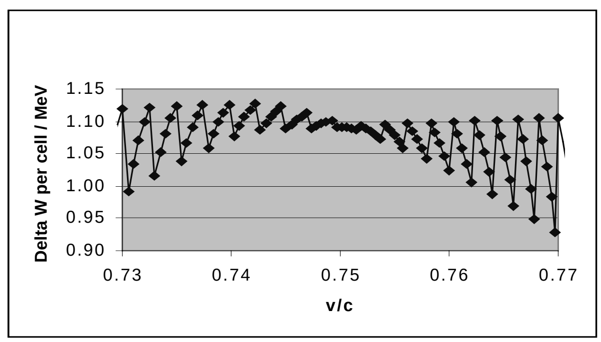


Figure 3: Energy gain per cell $\beta_\Lambda$=0.75 (crp. 480 MeV). The maximum phase $\phi$ of the centre cell is set to -20°.

The number of groups of identical cavities to be built should be as small as possible for an economic manufacturing. On the other hand, a criterion has been used to tolerate a maximum decrease of the transit-time factor of 5% at the ends of the groups of identical cavities. Hence, 5 different groups of identical cavities will be necessary to accelerate the beam in the linac from 70 MeV up to 1334 MeV. The geometric velocities for the 5 groups are $\beta_\Lambda$=0.353, 0.431, 0.526, 0.641, and 0.782. In a next step the energy gain throughout the whole family has been optimised by varying the centre velocity factor $\beta_\Lambda$. The result of this optimisation is shown in figure 4.

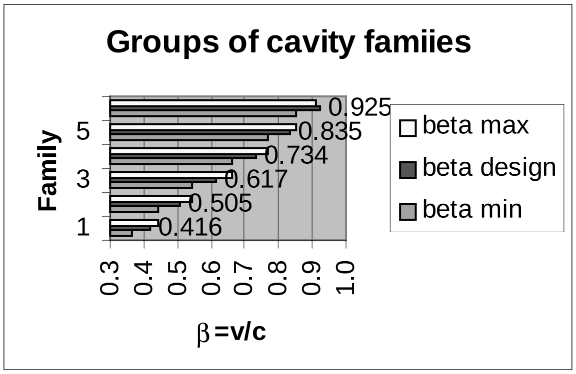


Figure 4: The centre velocity factor $\beta_\Lambda$ and the β-range for the cavities of the 6 families. The numbers are given for the centre velocity factor $\beta_\Lambda$

We will create two additional cavity groups at the upper end because most of the energy will be gained at β>0.75 (480 MeV). Figure 3 shows as an example The energy gain per cell for a group of identical cavities. The single-cell tracking method will be completed to include also power coupler and transverse beam dynamics aspects.

## 4 TRANSVERSE BEAM DYNAMICS

For the arrangement of the quadrupoles FODO-, doublet-, and triplet-focusing has been studied. The most simple focusing structure the FODO structure. We group 4 cavities between the focusing quadrupole F and the defocusing quadrupole D. The strength of the quadrupoles is constant all along the linac from 70 MeV up to 1333 MeV. The relative focusing force decreases with the increasing energy. The β-functions $\beta_x$, $\beta_y$ increase, the increasing beam diameter is compensated by the adiabatic shrinking of the beam proportional to $1/(\beta\gamma)$. β-functions are shown in figure 5 and the beam radius is seen in Fig. 6.

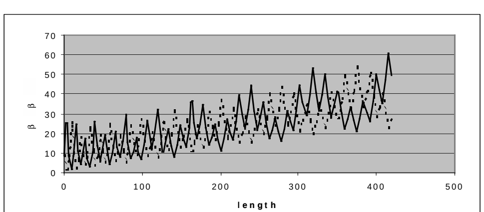


Figure 5: β-functions $\beta_x$, $\beta_y$ for the FODO-focusing in the linac. The quadrupoles are 20 cm long with a gradient of 1.8 T/m at a bore radius of 5 cm.

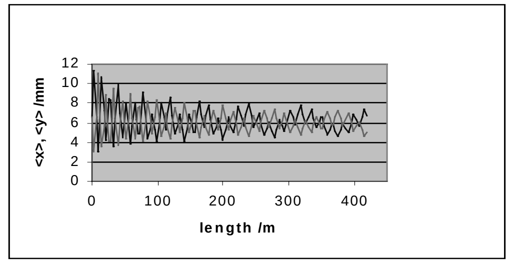


Figure 6: Beam radius for the FODO structure using quadrupoles with identical strength.

## 5 REQUIREMENTS FOR THE COUPLING COEFFICIENTS

The field flatness in the cells depends on β and the cell-to-cell coupling $K_f$, it is given in the formula.

$$\frac{\Delta E}{E_{acc}} = e^{\frac{t_{inj}}{\tau}} \sqrt{P \frac{4\beta^2}{(\beta+1)^2} \frac{R_{sh}}{Q} Q_L} \cdot \frac{\pi}{K_f\left[1-\cos\frac{\pi}{N}\right] \cdot Q_L E_{acc}}$$

For a 1% field flatness the $K_f$ is shown in figure 7

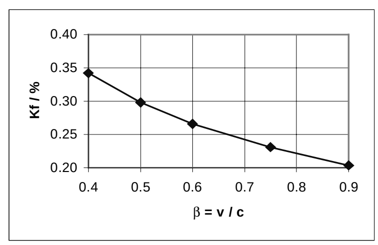


Figure 7: Cell-to-cell coupling factor vs. β. A field flatness of $\Delta E/E_{aac}$=1% has been taken for the N=5 cell cavity.

## 6 REFERENCES


[1] J.Kjems, A.D.Taylor, J.L.Finney, H.Lengeler, U.Steigenberger (ed.), "ESS - A Next Generation Neutron Source for Europe", Vol III, "The ESS Technical Study", Copyright: ESS Council, March 1997

[2] B.Aminov, A.Gamp, E.Haebel, H.Heinrichs, H.Piel, J.Pouryamout, Th.Schilcher, D.L.Schrage, G.Schulz, S.Simrock, C.H.Rhode, and R.Röth, "Conceptual design of the Superconducting High Energy Linear $H^-$-Accelerator for the Future European Spallation Source (ESS)", ESS 96-60-L, December 1996

[3] T.P. Wangler, "Principles of RF Linear Accelerators", Wiley series in beam physics and accelerator technology, 1998

[4] W. Braeutigam, S. Martin, E.Zaplatine, "Design Study for SC Proton Linac Accelerating Cavities", this conference.

[5] W.Diete, B.Griep, M. Peiniger, H. Vogel, P.Vom Stein, W. Braeutigam, "Superconducting Accelerating Test Modulee for the ESS", this conference.