DESIGN AND OPTIMIZATION OF THE ESS LINAC

M. Eshraqi
European Spallation Source, Lund, Sweden

Abstract

The LINAC of the European Spallation Source will accelerate the proton beam to its final energy mainly by using superconducting structures. Choosing the right transition energy between these superconducting structures as well as choosing the cavity length and number of cells which enhances the acceleration is of great importance. Two types of LINACs will be studied, a LINAC with superconducting quadrupoles and a LINAC with normal conducting, resistive, quadrupoles. The procedure to find the optimized LINAC will be described here.

INTRODUCTION

The European Spallation Source, ESS, to be built in Lund, Sweden, will use a high current proton LINAC to accelerate protons, required for generating high flux of pulsed neutrons using a spallation process. In the new design, compared to the 2003 ESS design [1], the average beam current is decreased by more than a factor of two to increase the reliability of the machine and also to allow a future probable power upgrade by increasing the current. To keep the beam power constant at 5 MW the beam energy has to be increased from the 2003 design values (5 MW, 1 GeV, 150 mA, 16.7 Hz) to 2.5 GeV.

In the new design LINAC delivers 5 MW of power to the target at 2.5 GeV, with a nominal current of 50 mA [2]. It is foreseen to include the ability to upgrade the LINAC to a higher power by increasing the current.

SUPERCONDUCTING LINAC STRUCTURES

Three families of superconducting structures will accelerate the beam from 50 MeV to 2.5 GeV. The first SC accelerating structure is a 352.21 MHz spoke resonator followed, after a frequency jump to 704.42 MHz, by two families of elliptical multicell cavities.

The SC LINAC is responsible for 98% of the energy gain and covers around 90% of the LINAC length. The purpose of this study is to find the optimum number of spokes and cells in each of these three families, as well as the best geometric beta, number of cavities per each period and finally the transition energy between the neighboring structures.

Since all of these parameters are dependent on each other the optimization has to be performed in the 11 dimensional space: 3D of β_gs, 3D of number of cells per cavity, 3D of number of cavities per cryo-module and 2D of transition energy between spokes to low β and from low β to high β. However, the number of cells in low β cavities is manually linked to the number of cells in high β elliptical cavities, reducing the degrees of freedom by one.

These parameters will vary depending on the cryo-module geometry, use of resistive or superconducting quadrupoles and sectorization of the cold LINAC. An example of the optimization, for the geometric βs of the cavities in 3 dimensions is presented in Fig. 1.

POWER, VOLTAGE, AND PHASE SETTINGS

Choice of Accelerating Gradients

To select a reasonable accelerating voltage is of great importance, since an over specified value which will not be reached will result to a LINAC which may look shorter, but will not be able to bring the beam to its final energy. On the other hand an underspecified value may result to a LINAC which will be unnecessarily long.

By fitting the equation 1 to the empirical points of Fig. 2, values of k_1 and k_2 constants will be found.

$$E_{acc.max} = \frac{E_{peak.surface}}{k_1/\beta_g + k_2 \cdot \beta_g - 1}, \tag{1}$$

where, $E_{acc.max}$ is the peak accelerating field, $E_{peak.surface}$ is the peak surface field, β_g is the geometric β of the cavity, and $k_1 = 1.95, k_2 = 1.15$ are constants, green solid line in Fig. 2.

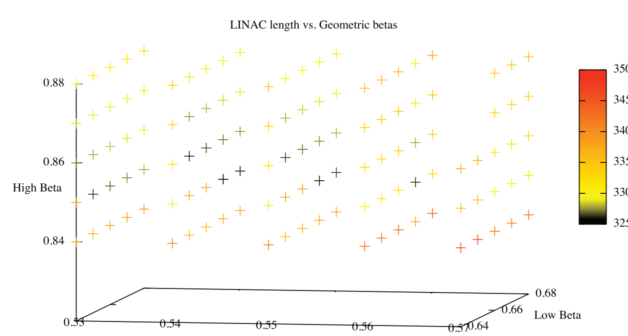

Figure 1: Result of optimization process, varying the geometric βs to optimize the LINAC length. The darkest + sign indicates the shortest LINAC, plot represents the study for the LINAC with superconducting quadrupoles.

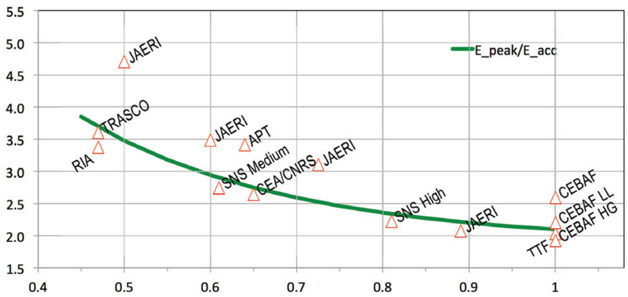

Figure 2: Ratio of the peak electric surface field to accelerating field vs. β_g. [3]. The green curve is a fit according to equation 1.

Power

Power is limited by the maximum power a coupler can deliver to the cavity. In case of a 50 mA beam, and an accelerating gradient of ≈ 20 MV/m, the required power to accelerate the beam would be ≈ 1 MW, for a cavity which is almost 1 m long. At such a high power, around 1 MW per coupler, rf windows have to be designed carefully due to the high thermo-mechanical stresses which they have to tolerate. A pair of such couplers capable of delivering up to 1.2 MW, at 50 Hz and for a 2 ms pulse have been built and tested in Saclay, France. [4]. In this study the power per cavity is limited to 900 kW to leave a safety margin.

Accelerating rf phase

Acceleration and bunching of the continuous beam of particles out of source starts in the RFQ at an rf phase of $-90°$ and then the phase gradually increases to $-20°$ at the end of DTL. In the spoke resonators, the accelerating phase, except for the matching cavities, starts at $-20°$ and increases to $-15°$ at the end of the spokes. Elliptical cavities will work on twice the frequency, i.e. 704.42 MHz, and if this frequency jump is not handled correctly a loss of longitudinal acceptance in the transition between these two structures may cause excessive emittance increase and particle loss in elliptical cavities. To keep the bucket size constant across the transition accelerating phase as well as the accelerating gradient are decreased in the first few periods of the elliptical cavities [5]. Later in the high β region the synchronous phase stays constant at $-15°$.

Phase Advance

Another boundary condition applied to the optimization process is the limit on the longitudinal phase advance per period. The upper limit chosen during this study is 80° per period, to allow for a minimum transverse to longitudinal phase advance ratio of 1.125.

OPTIMIZING CRITERIA

Amongst all the choices the total LINAC length is chosen to be the criteria for the optimization process. The reasons behind this choice are:

- Since the maximum power per each cavity is fixed, a shorter LINAC, requires the klystrons to be working on more similar power, which will save energy,
- The shorter the LINAC the more efficiently power is transformed from wall plug to beam energy, reducing the running cost of LINAC
- The LINAC tunnel will cost around 20% of the whole accelerator project [6]. A shorter LINAC requires less equipment and therefore the overall cost decreases.

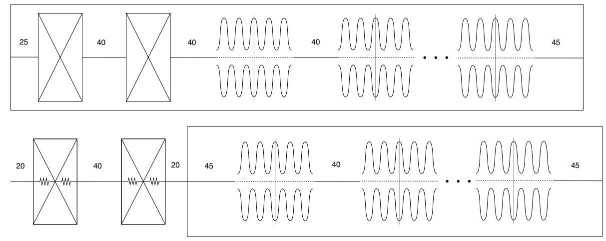

Figure 3: Schematic drawing of the cryomodules. Top: Cold quadrupoles. Bottom: Warm quadrupoles.

SUPERCONDUCTING QUADRUPOLES

The reason for choosing cold quadrupoles is that these quadrupoles can be housed inside the cryo-module with the cavities, and therefore a large number of cold to warm transitions will be removed, resulting in lower heat load in the cryogenics system. The lower power consumption of quadrupoles does not play a significant role in this selection since this can be offset by the required cryogenics power. However, having a long continuous cryo string requires a longer shut down period in case a cryo-module needs to be repaired.

The spacings defined in Fig. 3, though being studied before being chosen, are the preliminary values and are subject to change if cryogenics, diagnostics, or rf requirements such as extra heat load, lack of enough space for diagnostics or rf coupling between neighboring cavities dictates another value.

HYBRID DESIGN

A hybrid cryomodule architecture, not shown in Fig. 3, which provides a 2 K environment for the cavities, while allows for a transition between cryomodules in the sub-100 K region is studied. This hybrid design will generate a lower heat load with respect to a fully segmented design - while still providing easy access to individual cryomodules for maintenance and repair, and allows for temperature independent design of beam instrumentation and diagnostics, this design is studied in another paper [7].

RESISTIVE QUADRUPOLES

A LINAC using resistive (warm) quadrupoles is designed in parallel to the superconducting LINAC. Such a design is intrinsically segmented to cryo-modules with doublets of quadrupoles in between them.

The advantages of this LINAC are the shorter time to repair/change a cryo-module, higher precision in alignment of the quads, and the accessibility of warm quadrupoles. However the heat load will increase because of numerous cold to warm transitions. A schematic drawing of this layout is presented in Fig. 3. Since copper is the main source of radiation due to activation [8], if possible it is better to avoid copper in favor of other conductors, such as aluminum which has the same price/mho, for the quadrupole windings.

RESULTS

For both LINACs, with superconducting and resistive quadrupoles, the optimizations are performed by using equation 1 to calculate the field for each geometric β. The input energy to spokes is set to 49.5 MeV to compensate for a possible lower energy due to matching. In the spoke resonators an accelerating field of 8 MV/m is chosen, while for the elliptical cavities a surface peak field of 40 MV/m is used.

The code GENLINWIN [9] from CEA is used to calculate and find the optimized LINAC. The results of this study are shown in Table 1.

Assuming that the power delivered to a cavity is limited, when the accelerating field is decreased the number of cells per cavity can be increased in order to use the maximum of available power. However, increasing the number of cells will decrease the spring constant of the cavity, therefore for a fixed Lorentz force detuning, a 6 cell cavity will demonstrate oscillations with higher amplitudes.

On the other hand, if we fix the number of cells per cavity to 5 cells in the elliptical cavities to limit the number of trapped modes and other HOMs the cavity length, geometric β, increases by few percent to compensate this reduction in length and to use more efficiently the available power.

Exotic Designs

Two sets of exotic, single and triple β, LINACs are studied. In case of a single β LINAC the LOMs and HOMs have to be studied throughly, while a triple β design is not significantly more attractive, economic, than the baseline double β design and if the costs of R&Ds is included it may cost even more than the baseline [10].

SUMMARY

Two LINACs, one using superconducting and another one using resistive quadrupoles are studied. Both LINACs are designed to fulfil the diagnostics and cryogenics requirements. For each case two proposals for using either five-cell or six-cell elliptical cavities are made. A six-cell design would require less cavities, and consequently less rf equipments while it suffers from the higher probability of LOMs, HOMs and trapped modes, and it is less adaptable for a power upgrade, making the five-cell cavities, columns 1 and 3 in Table 1 the preferred solution.

Table 1: Optimized values for warm and cold quadrupole designs. The accelerating gradient varies as a function of β_g in the optimization process as in eq. 1.

	Cold Quad.		Warm Quad.	
	5 Cell‡	6 Cell‡	5 Cell	6 Cell
Spoke, β_g	0.53	0.51	0.52	0.51
Transition β	0.55	0.55	0.55	0.55
Cav./Per.×Per.	3×12	3×12	3×12	3×12
Lowβ, β_g	0.67	0.67	0.67	0.67
Transition β	0.77	0.77	0.77	0.77
Cav./Per.×Per.	3×13	3×12	3×13	3×12
Highβ, β_g	0.88	0.86	0.88	0.86
Cav./Per.×Per.	8×16	7×16	8×16	7×16
No. of Cav.	203	184	203	184
E_{out} (GeV)	2.5	2.5	2.5	2.5
Length (m)	327.4	323.0	329.3	325.2

‡ 5 and 6 are the number of cells in elliptical cavities, and the number of spokes are always 2.

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