VALUE ENGINEERING OF AN ACCELERATOR DESIGN DURING CONSTRUCTION

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Abstract

Value engineering is an important part of the process of designing and realising large-scale installations such as high power accelerators. This typically occurs during the design stage of the system, although such exercises may also be requested by funding bodies at later stages in order to manage project contingency. Naturally, the later this is done, the more challenging it becomes. In this paper, we report on a recently concluded Value Engineer-ing effort at the European Spallation Source. The chal-lenges presented by the initiation of such an exercise during the construction phase are discussed. In addition, we present and discuss the various options that we exam-ined, and indicate the philosophy and figures of merit used to narrow down these options. The final conclusion will be presented. A 40 M€ cost reduction was achieved by the accelerator project..

INTRODUCTION

The European Spallation Source (ESS) is being constructed and installed in Lund, Sweden. When completed, the facility will become a world-class neutron centre for physical and life sciences research. The machine consists of a high power linac delivering 2 GeV protons to a rotat-ing Tungsten target, where neutrons will be produced through spallation. The key high level linac parameters are shown in Table 1, while the main design blocks can be seen in Table 2.

During 2016 it became apparent that the contingency margins were not enough to complete the whole project as planned without considerable cost risk. Therefore, a value engineering exercise was performed, to decide how the project plan could be modified to still allow building a world-class facility with the funding constraints present. The current paper presents the results of the value engi-neering exercise for the ESS linac. The accelerator design itself is presented in [1].

ACCELERATOR VALUE ENGINEERING

A value engineering team was put together to decide on what to do and the following guidelines were followed:

1. First, identify pure savings, or things that can be done at reduced cost without impairing function.
2. Decide if there is room for de-scoping, and what this would mean for cost.
3. Decide on a scope recovery scenario at a later stage and how this would affect cost.

In this case, pure savings were identified and the challenging became how to de-scope without introducing unwanted problems. Making changes to a project this late in design/construction is difficult, but a decision was made that the best course of action was to follow a reduction of output power as a de-scoping strategy. As this implies a reduction of RF power sources and/or cavities, significant cost reductions can be achieved.

Table 1: Main Linac Parameters

Parameter	Design Value
Proton Energy	2 GeV
Beam Current	62.5 mA
Average Beam Power	5 MW
Beam Pulse Length	2.86 ms
Duty Pulse Rep. Rate	14 Hz
Duty Cycle	4 %

Table 2: Main Linac Design Blocks

Linac Section	Temp. [K]	Freq. MHz	No. of Cavities
LEBT	300	-	0
RFQ	300	352.21	1
MEBT	300	352.21	3
DTL	300	352.21	5
Spoke	2	352.21	26
Medium Beta	2	704.42	36
High Beta	2	704.42	84

DE-SCOPING SCENARIOS

If the reduction of scope can be met by lowering the average beam power, this could be achieved by reducing the current, reducing the final energy or the duty cycle. The following boundary conditions were established:

- No cancellation of orders that are already placed.
- No cancelling of cryomodule testing.
- No modifications of buildings and utilities.
- Plan for recovering of scope during operations.

With these conditions set up, it became obvious that two main scenarios could be followed:

A. Reduced beam current

B. Reduced beam energy

Scenario A: Reduced Beam Current

When the beam current is reduced, less RF is needed to power the cavities. ESS looked at halving the beam cur-rent, which halves the need for RF amplifiers and HV modulators. This has advantages and disadvantages:

+ Reduces the number of RF sources

- description Couplers need RF matching
- Influences whole linac
- Recover scope must be done in one complex and costly step

With reduced current, one could feed two adjacent RF cavities with one RF source. If the beam was relativistic, these cavities could be fed at a constant phase difference which could have been achieved by adjusting the length of the waveguides. For a linac like ESS where the final beam energy is only 2 GeV, there are not many cavities which could benefit from this scheme. Any energy change in the upstream parts of the linac would break the con-stant phase difference between these coupled cavities (see Fig. 1), while any temperature change in the waveguides could also add to the phase difference (see Fig. 2).

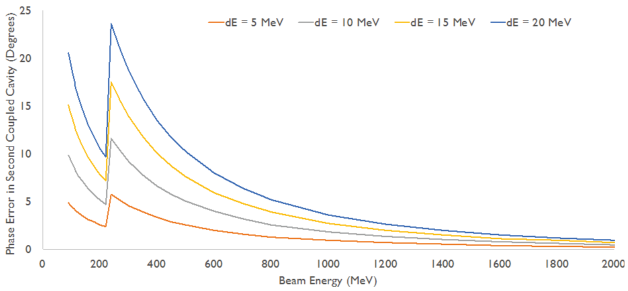

Figure 1: Phase shift in the second cavity of a pair of cavities fed by the same RF source due to the change in the energy of the input beam.

In such a scenario, also the field difference between neighbouring cavities, fed by the same RF source, could be significant. If there are no other means to adjust the fields individually, the difference in the external Q of these cavities will affect the operating voltage:

$$V^2 = \frac{1}{4}\frac{R}{Q}Q_L P_f$$

where QL is the loaded quality factor of the cavity, PF is the forward power to the cavity and V is the voltage in the cavity. Such variations of the QL could cause up to 36% field difference between two cavities fed by the same source when considering the manufacturing tolerances on the ESS elliptical cavity couplers. The variation of the transit time factor from cavity to cavity could lead to an additional 8% increase. This would force the field in the cavities to be reduced such that the field in the cavity with the highest coupling does not exceed the operating voltage of that cavity.

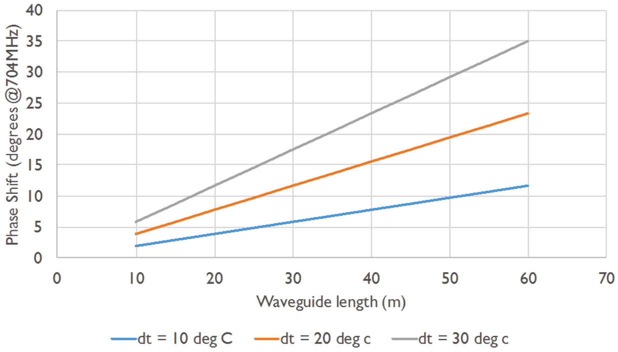

Figure 2: Phase shift in the second cavity of a pair of cavities fed by the same RF source due to the temperature variation of the waveguides.

To avoid all these problems, we had to add an adjustable phase shifter to each leg of the wave guide using multi-stub tuners. Then each leg needed a circulator and a load, and the LLRF should have been modified to control the two coupled cavities. From the commissioning and operations point of view, the setup would become more complicated as any phase scan would be affected by the unknown (variable) phase between the cavities.

This scenario was evaluated and considering the additional equipment and the R&D needed, the cost saving is not as significant. The recovery is very difficult as almost all the cavities should be equipped with the missing half of RF power and the RF distribution system needs to be reconfigured. Adding the complications on the commissioning and operations, plus the impact on the reliability and availability of the linac, this scenario was discarded.

Scenario B: Reduced Beam Energy

For a linac, reducing the beam energy translates into fewer number of accelerating cavities, requiring fewer RF sources, modulators, etc. If scope recovery is essential, this scenario leaves two main options:

1. Defer only the purchase of RF sources for the unpowered cavities.
2. Defer also assembling the unpowered cavities.

Powering a reduced number of cavities and keeping all other parameters intact plays to the strengths of a linac. The addition of extra acceleration in the future is simple, there is little or no effect on other systems, scope recovery can be done gradually as the unpowered cavities could be added to the chain of accelerating cavities one after an-other. But installation of each cavity (they come in groups of four assembled in a cryomodule) would require a lengthy process of installing a local clean room, removing the temporary

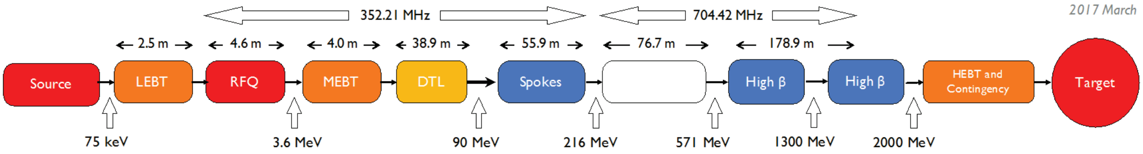

Figure 3: Block diagram of the ESS linac components, warm coloured boxes are the normal conducting section of the linac and the cold coloured ones are the superconducting parts. The two phases of the high beta cavity installations and the transition energies are also shown.

drift tubes and then installing the cryomodule. Instead one could install all the available cryomodules in one step since all the evaluations showed that stopping and restarting the cavity and cryomodule production is neither cheaper nor logistically feasible. It was chosen to not defer the assembly/production of cryomodules. Stopping production in the specialised facilities used for cryomodule assembly and later restarting, would risk greatly increasing the cost and introduce risks of getting more cavity performance variations. At ESS the RF distribution from the gallery to the tun-nel passes through the stubs. Each stub houses up to eight waveguides and the cables. These stubs will be filled with radiation shielding material after the installation of the waveguides and cables. In order not to remove the shield-ing material for the installation of the waveguides of the deferred RF stations, the part of RF distribution which is inside the stubs will be installed with the rest of the waveguides and so are the cables through these stubs.

Within this scenario, another scheme which would use all the cavities was evaluated. The cavities beyond 1 GeV where the changes in velocity per cavity were negligible were coupled together without a controllable phase difference between cavities and were fed by the same klystron and were operated at reduced voltage to keep the power within the limits of the klystrons. The advantage would be that one could get closer to the operational limits of the klystrons and gain a higher power compared to reducing the energy, as the limits of the cavity voltage and coupler power handling are not reached. After evaluating the cost deferred by this method compared to the reduction in the number of final neutrons, this sub-scenario was also dis-carded.

Another aspect to consider is the interaction of the unpowered cavities with the beam and whether to keep such cavities at room temperature or cool them down to the cryogenics temperature. Leaving the cavities at room temperature will reduce their Q value to the order of (1E4), resulting in a bandwidth of 70 kHz. To ensure that these cavities are not interacting with the beam, the cavities have to be detuned by more than ten bandwidths. Due to thermal expansion of the cavities the frequency is shifted by >1 MHz, which is enough to avoid any interactions with the beam. Manufacturing tolerances could cause frequency shifts and tuning the cavity for the fundamental mode could result in a different distribution of the higher order modes (HOMs). The exact frequency of the HOMs, at room temperature can only be measured after tuning of the manufactured cavities.

An alternative solution is to cool down these cavities to their operating temperature and then detune them by a few bandwidths. The advantages are that at low tempera-tures the Qs of the cavities are much higher and the bandwidths are very narrow, both for the fundamental mode and for the HOMs. This would require the detuning functionality of the LLRF system for these units.

EVALUATION AND PROPOSAL

After evaluating all the scenarios, it was decided to focus on de-scoping by powering fewer high beta cavities. By powering only 44 of the 84 high beta cavities, a proton energy of 1.3 GeV can be reached. This will give a neutron yield equal to 70% of the number of neutrons at full power. The beam power is reduced to 3 MW. The new linac layout showing the two phases of high beta cavity installation can be seen in Fig 3.

The initial set-up of the linac will thus involve removing the RF for the last 10 cryomodules in the high beta linac. These findings were presented to the Technical Advisory Committee which recommended that these cryomodules are delivered to Lund and installed in the tunnel.

Each of the four high beta cavities, housed in a com-mon cryomodule is fed by a separate klystron or IOT. A decision on the final choice will be made once the ongoing tests of the prototype IOTs are completed. All four RF tubes are powered by a common modulator and the scope recovery will be done in steps of one cryomodule (four cavities).

CONCLUSION

A value engineering team analysed the ESS linac design to find cost savings by reduction of scope. The proposed scenario is a proton energy decrease from 2 GeV to 1.3 GeV with a corresponding reduction in power from 5 MW to 3 MW. The reduced scope still yields 70% of the neutrons expected at full operational parameters. The cost reduction is achieved by postponing the procurement and installation high power RF sources for the last 40 high beta cavities of the linac, with savings of 40 M€.

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REFERENCES

[1] M. Lindros *et al.*, "The ESS Project", submitted for publication.