COMPENSATION OF EFFECT OF MALFUNCTIONING SPOKE RESONATORS ON ESS BEAM QUALITY

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Abstract

The LINAC of the European Spallation Source will accelerate the proton beam to 2.5 GeV, 98% of this energy is gained using superconducting structures. The superconducting LINAC is composed of two types of cavities, double spoke resonators and five-cell elliptical cavities. The LINAC, which is five times more powerful than the most powerful existing LINAC, and the spoke cavities that have never been used at such a scale make it necessary to study the effect of one or a few spoke resonators not functioning properly and to find a solution where the defect is compensated by retuning of the neighboring cavities.

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]. The repetition rate of the LINAC is 14 Hz and the pulse length is 2.86 ms, resulting in a 4% duty cycle . It is foreseen to include the ability to upgrade the LINAC to a higher power by increasing the current.

This study will consider the failure of a single cavity in four cases, failure in one of the cavities in the first cryo module, failure of the cavity with highest energy gain, and failure of the last cavity which is used for matching the phase advance in spoke resonators to the low β section, Fig. 1. Then three cases where both cavities of a cryo module fail will be considered, again in the three regions of initial matching, high energy gain, and final matching. The latter study will be useful for defining the powering scheme of cavities.

SUPERCONDUCTING STRUCTURES

The ESS LINAC is composed of a normal conducting front end which brings the beam to an energy of 50 MeV, using a 352.21 MHz RFQ and a three-tank DTL. The schematic layout of ESS LINAC is shown in Fig. 2. At 50 MeV the beam energy, velocity, is high enough to switch to a structure which does not follow the beam velocity in a cell-to-cell manner. One of the choices amongst this type of structures is the superconducting half wave spoke resonator. Some of the advantages of such a structure are, large transverse acceptance, few coupled cells which enhances the longitudinal acceptance, their relative insensitivity to microphonics, and low power consumption to name a few. However, at higher energies where elliptical cavities could be used, efficiency of spokes is not as good as that of ellipticals, and multi-cell elliptical cavities are favored. These elliptical cavities are working at twice the frequency, 704.42 MHz, and will bring the beam to its final energy in two steps, low β cavities increase the energy from 188 MeV to 606 MeV and high β cavities further to 2.5 GeV. The transition energies, as well as the geometric β of the cavities, number of cells per cavity and the number of cavities per period are optimized for the ESS current, power and energy range [3].

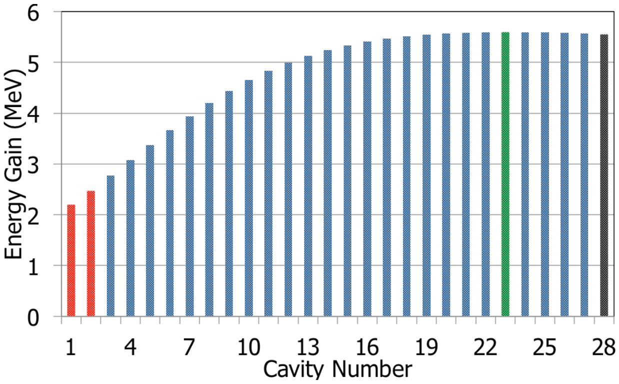

Figure 1: Energy gain in spoke cavities versus cavity number. Red: cavities in first cryo-module, Green: cavity with highest energy gain, Black: cavity used in matching.

SPOKE RESONATORS

There are 14 spoke cryo-modules in the present design of the ESS LINAC, each of them housing two double-spoke cavities which are sandwiched between two superconducting quadrupoles, one at each end of cryo-module. One of the main reasons for choosing a superconducting spoke structure for the low energy part of the LINAC is the ability to tune the individual cavities independently. The ability to tune the phase and voltage of each cavity, three accelerating gaps, makes the LINAC flexible for rematching in case

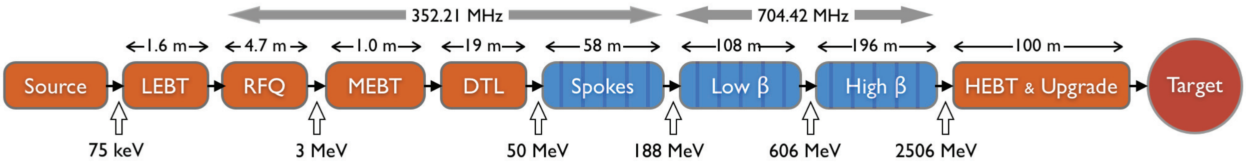

Figure 2: The schematic layout of ESS LINAC. Not to scale.

of loss of energy gain in a cavity. However, such a failure causes the beam to reach the downstream quadrupoles and cavities with wrong energy, resulting in a huge mismatch and particle loss. To avoid this unwanted effect, the two neighboring cavities and one pair of quadrupoles at each side of the affected cavity are adjusted to match the beam locally. Since the LINAC is designed to have a smooth phase advance along different sections and on matching sections [4], a locally matched beam will be matched for the rest of the LINAC.

PROCEDURE

To simulate the effect, $100,000$ macro-particles, with a total current of 50 mA, are tracked in the LINAC using the code TRACEWIN [5]. Input beam emittances are the output of drift tube LINAC, DTL. However, the beam is matched to superconducting LINAC by adjusting the beam parameters, not the LINAC. To see how the effect of a cavity failure propagates and evolves all along the LINAC the beam is tracked to the end of superconducting LINAC where it reaches almost 2.5 GeV when there is a failed cavity.

The ESS requires a reliability of higher than 95% for the whole site, which requires a higher reliability for LINAC. Still one trip of longer than 10 sec per day is permitted in the design [6]. Such a value is still far more relaxed than the requirements for an Accelerator Driven System, ADS, which needs sub second trip correction schemes [7]. Including this higher tolerance against failures, ESS can use a correction scheme which does not necessarily correct the energy gain of the beam and performs the matching on the fly. Therefore another fault tolerance scheme where the machine is turned off upon a failure and then is restarted in the retuned state can be used.

A failed cavity, power supply, etc, in the first order would nullify the energy gain in that part of the LINAC. The best hypothetical solution would be increasing the voltage in upstream or downstream cavity. This will guarantee the right energy gain and exact arrival time in all the downstream cavities. However, it is not practical to leave a 50% margin in the cavities, or to increase the voltage by a factor of 2. Consequently in this study when a cavity fails, the phase of the neighboring cavities is adjusted to match the beam in the longitudinal phase space to the rest of the LINAC, but to preserve the longitudinal acceptance, the phases of these cavities are moved farther from the crest, enhancing the loss of energy gain. In another failure correction scheme, a 30% margin in the field of the cavities has been considered during the design stage. Such a margin allows to correct the energy as well as performing a local matching, and does not require adjusting the phases of all the downstream cavities [8]. Theoretically, the larger the local compensation area, the less margin in the field of cavities is needed.

The wrong energy and rigidity of beam added to the now nullified rf defocusing results in a transverse mismatch of the beam as well. To tackle the transverse mismatch two pairs of quadrupoles, one upstream and one downstream of the incident are re-adjusted to re-smooth the phase advance variations locally, and since the LINAC is designed to have smooth phase advance variation the beam will be matched for the rest of the machine.

A factor which must be considered is that though in the simulations the beam is matched using only two cavities and two pairs of quadrupoles, in reality the timing of all the downstream cavities must be adjusted, since a 5 MeV loss in the energy out of spoke resonators can cause a phase difference of more than $30°$ in the high energy part of high β section.

RESULTS

Statistically all the 28 cavities and their power supplies in the spoke section have the same chance of failure. However, to decrease the number of cases which must be studied these cavities are divided in three groups, the low energy end matching cavities, the high energy gain cavities, and the high energy matching cavities. In a more physical perspective, the first cavities after warm to cold transition are more prone to contamination and reduction of performance. Therefore in this study the cases where each of the cavities in the first cryomodule fails individually is studied.

First cavities

The worst case is when the first spoke cavity fails, not only because the beam has its lowest energy in the section, but also because the longitudinal properties of the beam out of DTL are mechanically fixed by the geometrical design of DTL, forcing the two downstream cavities to act in order to match the beam.

On the other hand, a failure in the second cavity causes the least damage to the quality of the beam, Table 1. This can be explained by the low energy gain in this cavity as well as the possibility to readjust the phases of the two neighboring cavities.

High energy gain cavities

The cavity where the reduced velocity, β, of the beam is close to the optimum β of the cavity results in the maximum energy gain per cavity in the spoke region, green bar in Fig. 1. A failure in this cavity would cause around 5 MeV of energy loss, at the end of the LINAC. However, since the failure can be treated by the neighboring cavities, the beam quality degradation is least in this case amongst the four studied cases, Table 1. This can be explained by the minimum acceptance shrinkage in this case.

Last cavity

At the end of the spoke section, there is a frequency jump to twice the frequency, 704.42 MHz. During this frequency jump to preserve the size of the bucket, synchronous phase of the cavities in the elliptical region is increased, towards more negative values, by a factor of two. Then the voltage in the elliptical cavities is reduced to keep the phase advance variation per meter in longitudinal phase space smooth. Upon the failure of the last cavity, the fields must be adjusted again which causes a further loss of energy gain, and resulting in maximum energy loss in case of last cavity failure.

Two cavity failure

Three cases where at the same three locations, initial matching, high energy gain, and final matching both cavities in the same cryo-module are failed together is studied. The outcome of this study would be useful for different powering schemes of the cavities, Fig. 3. Simultaneous failure of both cavities in a cryo-module can not be corrected locally and needs not only re-adjusting of the phases of the downstream cavities, but also a transverse rematching at transition between structures. Unacceptable particle losses in the downstream structures will occur in this case. Increasing the number of corrector cavities from 2 to 4 can not improve the situation, though a reconfiguration of all the cavities and quadrupoles will improve the beam quality and transmission.

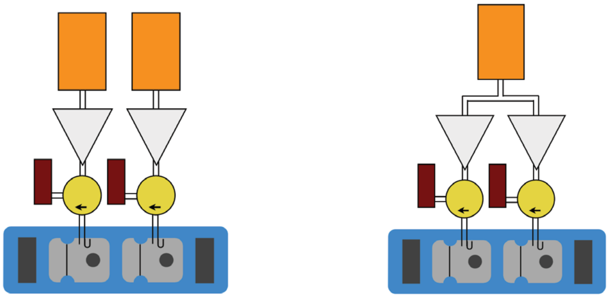

Figure 3: Two of the possible schemes for powering the spoke cavities. Left: One modulator per klystrons, Right: One modulator feeding two klystrons.

CONCLUSION

Cavity and power supply failure in the spoke region is studied for four cases which cover the whole range of cavities in the spoke region, two in the warm to cold transition, one in the high transit time factor region and a fourth one in the final matching to downstream structure. All the four cases are corrected using two cavities and two pairs of quadrupoles. However, the reduced energy of the particles of the beam would affect the arrival time in the downstream cavities and to fix it phases of all the downstream cavities must be re-adjusted. Excluding this error in the arrival time, not included in this study, the beam emittance is diluted not more than 25% in the worst case, with no induced losses. A simultaneous failure of both cavities in a cryo-module can not ne corrected with this method, even if the number of corrector cavities is increased to four.

Table 1: Effect of single cavity failure.

	Cav. 1	Cav. 2	Cav. 23	Cav. 28
$\Delta\epsilon_T^*$	25%	2%	12%	23%
$\Delta\epsilon_Z$	12%	1%	6%	3%
ΔA^* (Acceptance)	52%	54%	67%	56%
$\phi_{fail} - \phi_{nom.}$ [°]	-24	-19	-15	-72
Energy$_{out}$ [MeV]	2499	2499	2496	2495

$^*\Delta\epsilon = (\epsilon_{fail}/\epsilon_{nom.} - 1), \Delta A = A_{fail}/A_{nom.}$

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