RELIABILITY OF SUPERCONDUCTING CAVITIES IN A HIGH POWER PROTON LINAC

N. Pichoff, H. Safa, CEA Saclay, DSM/DAPNIA/SEA, 91191 Gif/Yvette, France

Abstract

Future high power proton linear accelerator projects are relying on the use of superconducting radiofrequency (SCRF) accelerating cavities. A great concern is given to beam loss (or even beam interruption) as it may have dramatic consequences. Long term and safe target operation is requiring very high reliability with unprecedented low number of beam trips. Therefore, fault conditions of the superconducting part have to be carefully analyzed. Fault scenarios are here envisaged from the beam characteristics and accelerator operation point of view. Solutions are proposed dealing with major fault conditions of SCRF cavities and indicating when beam interlocks are actually unavoidable. Whenever beam can be maintained even following a component failure, the overall reliability of the accelerator is enhanced. The impact on the accelerator design and RF distribution scheme is discussed.

1 INTRODUCTION

In a recent workshop on the reliability of high power proton accelerators (HPPA) [1], a great concern was expressed regarding the number of beam trips allowed for different applications. One major issue was the target for the nuclear waste transmutation demonstrator (ATW type projects). Due to the fatigue in the material core, the requirement was to keep the number of accelerator beam trips lower than 3 per week. As the core induced stress is related to a temperature variation, this implies a rather low process. Only beam trips exceeding one second were identified as being harmful. Therefore, short beam stops (in the ms range) will not be considered here as beam trips. The above requirement is still very aggressive. The number of beam trips on actual machines is at least two orders of magnitude higher (a couple per hour).

However, a distinction should be made between the availability, which is the relevant parameter for physics accelerators, and the reliability. A large number of beam trips, if not leading to a long time to repair, will not affect the overall availability. And until now, availability is the major concern on facilities. On the other hand, the reliability will ask for a low number of beam trips, regardless of the machine downtime. Therefore, this issue may lead to some specific features in the accelerator design. First, large margins should be taken on every critical parameters, as will be shown in this paper. Second, redundancy will be very important. Finally, the design should favor easy control operation, even at the expense of a higher investment cost. Unlike physics machines, these accelerators should be considered as of industrial kind. Higher performance components should be primarily used to improve reliability whenever possible.

2 THE SUPERCONDUCTING CAVITY

In this paper, focusing will be directed towards the high-energy part of the accelerator using superconducting cavities. An example of typical layout can be found in earlier papers [2].

2.1 Beam Loading

The beam loading is the most important parameter. A detailed analysis is given in ref. 3. The time variation in a SCRF cavity is dominated by the external coupling Q_{ext} from the fundamental coupler:

$$Q_{ext} = \frac{|V_c|^2}{2\left(R/Q\right)P} ,$$

where V_c is the cavity voltage, P the RF power delivered to the beam and (R/Q) the usual shunt impedance. The filling (and decreasing) time of the cavity is therefore $\tau = Q_{ext}/\omega$ giving a few hundreds of µs at a frequency of 704 MHz. This is the time constant at which the field decreases (exponentially) in a cavity when the RF is shut down. It is also the time to establish a given field in the other neighboring cavities for compensation. The second important parameter to consider here for a non-relativistic proton beam is the phase change along the linac. If in a cavity the field is down, a loss of energy gain at the entrance of the following cavity results. This energy loss translates into a phase slip equal to $\delta\phi = 2\pi\left(\frac{d}{\lambda}\right)\left(-\frac{\delta\beta}{\beta^2}\right)$, increasing with the distance d from the faulted cavity. If not compensated, this phase can rapidly lead to a beam loss along the linac (30 degrees/m, see 3.1).

2.2 Fault Scenarios

Failure can occur in many components of the superconducting linac. The main envisaged are the RF system, main coupler, field emission, vacuum leak, quench and cryogenics. A thorough discussion of failures can be found in ref. 4. Quenches are avoided by taking margins in the cavity field performances. Cryogenics failure can be minimized using redundant components. If field emission occurs, or if a weak leak is detected, the cavity field can be slowly decreased. An important leak would probably require a beam stop, no matter what. However, the most probable failure seems to be the RF system and/or the main power coupler (RF tube and windows). As a consequence, the RF is down at the cavity. In the following, beam analysis deals with ways to overcome the weak reliability of the RF system.

2.3 The RF system

The RF distribution is a key element in the overall reliability. It consists of power supplies, power tubes, RF control and all ancillary equipment (circulators, loads, guides, couplers, drivers,…). A RF source consists of a full setup including one amplifier that can deliver RF power to one or many cavities through the main power coupler. Usually, cost and availability of power sources drive the RF scheme. Cost decreases with increasing power unit as $C_{/W} = 1.0 + 200/P_{kw}$. It varies typically from 2.0 /W down to 1.0 /W. Around 40 % of the cost is coming from the power supply (the RF tube contributes for 20%). Therefore, to minimize cost, a single power supply can distribute the high voltage to several RF sources.

However, cost is not the main issue here. Reliability will definitely favor the use of a single cavity per RF power source, even though the power needed is relatively small (thus increasing the cost per Watt). In doing so, a much better control of the cavity phase and amplitude can be obtained. Moreover, the overall reliability is improved because only one cavity will be idle if a RF system fails.

On the amplifier choice, klystrons are generally used. But if the power needed is in the kW range, solid state amplifiers are preferred, even though their efficiency is lower. Recently, Inductive Output Tubes (IOT) are catching up. These tubes are very widely spread in industry and currently used for TV transmitters. They can deliver nowadays about 100 kW of RF power in CW mode. Active development in tube industry is now aiming at the 300 kW range. IOTs offer many advantages over klystrons. Due to the direct bunching of the beam, very high efficiencies can be achieved. As an example, a 300 kW IOT would be able to exceed 75% in efficiency. Moreover, this efficiency is still quite high when the amplifier is operated in a back-off regime (reduced output power). In fact, this is always the case for accelerators. RF sources operate generally at 70% to 80% of full capability depending on margins. Therefore the efficiency gain of an IOT compared to a klystron in real operation is even higher than at saturation (*Figure 1*). Another advantage of the IOT is its very simple maintenance and replacement. The cavity is separated from the tube. If a tube fails, it can be replaced in a few minutes without removing the cavity. Finally, IOTs operate at lower voltages (35-50kV) where power supplies are much easier (and cheaper) to build.

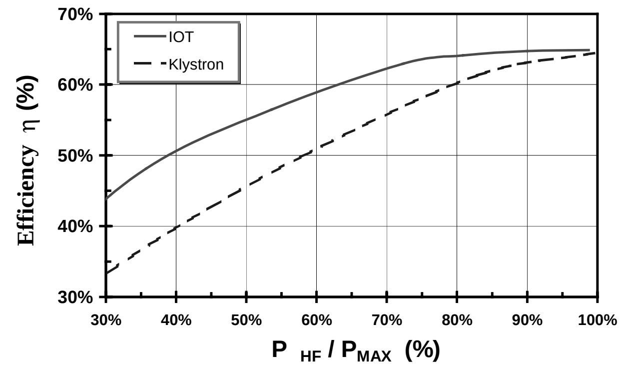

Figure 1- Compared efficiency between an IOT and a klystron.

3 TRANSIENT ANALYSIS

Let's assume the RF system fails at a cavity position where the beam has an energy of 205 MeV. The field amplitude and phase in this cavity, as well as the energy gain and the synchronous phase are changing with time according to *Figure 2*. The field phase, referenced to the linac designed parameters, is –30° before failure. As the detuning time is much larger than the filling time τ, after reaching the steady state, the beam loses in the cavity the same amount of energy it should have gained.

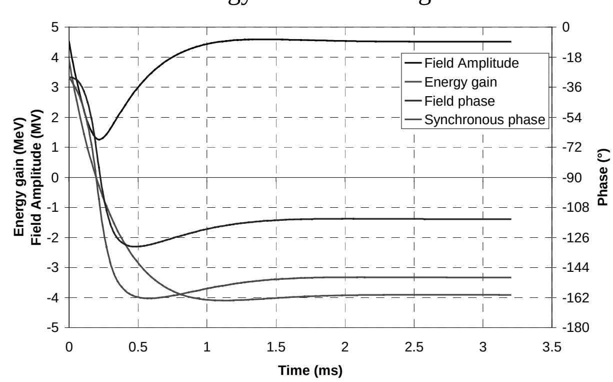

Figure 2- Transient of the field amplitude and phase, energy gain and synchronous phase in a faulted cavity.

3.1 No Compensation

First, field amplitudes and phases will remain unchanged in the SCRF cavities. But after a short time (140 µs, corresponding to a reduction in energy gain from 4 MeV to 1 MeV), the beam leaves the separatrix and is no more accelerated. One way to avoid this problem, is to lower the synchronous phase and the energy gain per cavity of the linac design. But this will increase the linac length and cost.

3.2 Reaction with a beam stop

When a cavity is idle, a new set of fields amplitude and phase in the remaining cavities has to be re-calculated to allow proper transport of the beam through the linac. But during the fall-down, it is impossible to set immediately the steady state fields in the cavities without losing the beam. This is mainly due to the large phase change induced by the lack of beam energy in the cavities downstream from the idle cavity. If the beam is stopped, the proper set of cavity fields (amplitude and phase) can be applied onto the unloaded cavities within a few number of filling times. Once the beam is switched on again, incident powers have to be changed in phase and amplitude to compensate for the beam loading. This is some sort of new commissioning of the linac. The main disadvantages of this solution are:

- The beam stop can be dangerous for the target, but it can be within ms range.
- The procedure could be very difficult to apply without a full beam restart, requiring a much longer time.

3.3 Localized Compensation

Because the aim is to keep the beam on the target without any interruption, the preceding solution is not fully satisfactory. Due to the large phase slip per unit length of a beam having the wrong energy, it is impossible to use directly a cavity far from the failing one for compensation. However, as the phase slip for the neighboring cavities is still not important, it is possible to use these to make a local compensation.

Using n^- cavities preceding the failing cavity (labeled n_0) and n^+ cavities following it, the particle can recover the right energy and phase at the exit of cavity number n_0+n^+. The time evolution of the field phase and amplitude in the compensating cavities have to be calculated from which the incident power phase and amplitude evolution can be deduced. As an example, a failure in cavity number n_0=40 at 205 MeV can be compensated using 2 cavities placed before and 3 cavities placed after. *Figure 3* shows the time evolution of the incident power in the cavities. Note that 70% of extra RF power is needed in cavity number 41 to have a perfect compensation at any time. In the steady-state regime (after a few ms), the extra power needed is reduced to 60%. Setting directly this RF power in the cavity will save 10% power. In that case the beam does not keep the exact final energy during a few ms, but will still manage to go through without loss (*Figure 4*). Once the steady state regime is reached, the extra-power can be progressively distributed over all the cavities. If the cavity can be detuned fast enough (within a filling time τ), only 30% of additional RF power is needed. Using more cavities to compensate the field will also reduce the extra RF power installed per cavity.

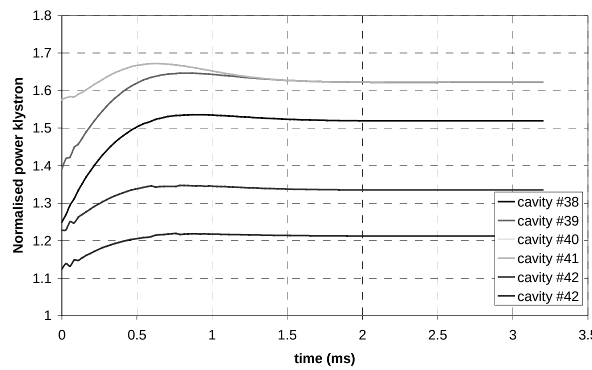

Figure 3 : Klystron RF power for an ideal compensation.

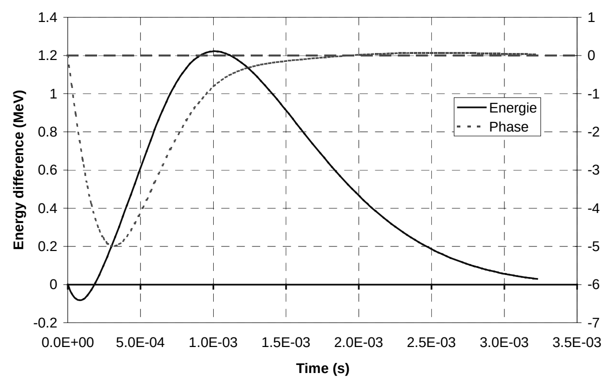

Figure 4 : Evolution of the final bam energy and phase with time in the case of a local compensation.

4 CONCLUSION

It has been shown that it is possible to cope with some frequent failures in superconducting high power proton linacs without shutting down the beam. Provided the use of a single cavity per RF source, redundancy and allowing for margins in the cavity fields, a solution is found to maintain beam if the RF system fails. Using the long time constant of SCRF cavities, a fast compensation of cavity phase and amplitude can preserve the beam through the linac. This is done at the expense of additional RF power installed on each RF source. It could help achieving the goal of reducing the accelerator beam trips to less than 3 per week.

REFERENCES

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