PERFORMANCE LIMITATIONS OF TESLA CAVITIES IN THE FLASH ACCELERATOR AND THEIR RELATION TO THE ASSEMBLY PROCESS

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Abstract

Several accelerator modules with superconducting TESLA cavities have been assembled for FLASH at the TESLA Test Facility (TTF). The performance of these structures is reviewed and an attempt is being made to correlate their performance to information about the assembly process. In some cases a degradation of performance could be attributed to problems in this process. The introduction of additional quality control (QC) steps improved accelerator module performance.

INTRODUCTION

The layout and design of the TESLA cavities has been discussed extensively in other publications [1, 2, 3]. The manufacturing and preparation processes are also described there. Papers discussing the more recent advances on surface preparation processes are also available [3, 4]. In this paper, integration of individual cavities towards a full accelerator module containing eight cavities and a magnet package is reviewed.

The assembly of accelerator modules consists of many steps:

- Preparation of cavities for acceptance test
- Welding of the helium tank to the cavity
- Preparation of the cavities for high-power operation
- Assembly of the string of cavities in the clean room
- Assembly to the cold mass and insertion in to the cryostat vessel
- Assembly of the warm part of the high power coupler
- Assembly of the module to the accelerator

These steps will be described in another paper in much more detail [5].

PERFORMANCE OF ACCELERATOR CAVITIES IN THE FLASH LINAC

In this paper the performance of cavities of all modules assembled for FLASH is taken into account apart from the very first module and the special module for the superstructure which are considered as prototypes. In total seven modules have been built. In some cases several components e.g. the cryostat vessel but also the accelerating cavities have been re-used. The modules are named in their sequence of first assembly: M1, M2, M3, etc. . If a module has been reworked e.g. cavities have been exchanged, a star is added to its name e.g. M1*. In this paper the cavities will be named e.g. M2C6, which denotes the sixth cavity in module M2.

In the FLASH linac the cavities have to be operated in the pulsed mode to keep the heat load on the superfluid helium system within acceptable limits. The RF power of about 210 kW per nine-cell cavity (for 25 MV/m) is transmitted through a coaxial power coupler.

Due to the strong overcoupling in the accelerator module the Q_0 has to be calculated from the heat transfer to the helium bath which can be measured only with large errors at low fields. Due to the long time needed for these measurements the full Q(E) curve of each individual cavity in the accelerator is not known. The field, at which the cavities quench, and in some cases also onset gradient of field emission is known. For the most recent modules Q(E)-curves for the full module are available.

Normally the RF power is equally distributed to the cavities leading to the same accelerating gradient in the all the cavities. With this type of distribution the worst cavity limits the full accelerator module. Therefore less performing cavities must be detuned during the measurement to find the limits of the better ones. In some cases the available RF power was not sufficient to find the limit of the cavities.

The data (Fig. 1and 2) shows several interesting features. First of all, some cavities perform well above the TESLA-500 or XFEL specification of 23-24 MV/m with a high Q_0. In the modules M4 and M5 ten cavities could be tested up to 30 MV/m (Fig. 1 – data points overlap). These cavities have been subjected to etching. Another cavity in M2*, which was electropolished, performed at 35 MV/m with a quality factor close to 10^{10}.

Additionally, the modules of the most recent cryostat type (M4, M5) have an operational gradient which fulfils the specifications of TESLA-500 or the XFEL (Fig. 2). The performance spread of the cavities in those modules is relatively small. On the other hand, there is module M3* which does not perform at a level expected.

CRITICAL VACUUM ASSEMBLIES

The cryomodule assembly has 3 vacuum systems: Beam vacuum, coupler vacuum and the isolation vacuum for the cryostat. In addition, several helium lines are part of the modules. All these different systems need to be free of leaks for several reasons. A leak to the beam or coupler vacuum might result in a contamination of the cavities due to particulates or gas layers or a more difficult RF conditioning of the couplers. A leak in the isolation vacuum can lead to enhanced cryogenic losses. The same would apply for a leak in the helium system.

All vacuum systems are checked for leaks at various stages during the assembly process. The experience at TTF has shown that this can lead to leak-free modules: The modules of the most recent type are free of leaks (M4, M5). The known leaks are listed below.

- Isolation vacuum to beam vacuum leaks

Several leaks between beam vacuum and isolation vacuum have been observed. It turned out that during the first assemblies of the modules the feedthroughs for the electron detection at the coupler and the RF signals of the

BPMs were not thermally cycled before installation into the modules. This was the major source for leaks in FLASH. In total 8 leaks were located at those feed-throughs: 5 at the BPM feedthrough in modules M2(4 leaks) and M3(1 leak), 3 at the coupler electron pickup (M2C6, M3C2 and M3C8). In one single case the flange of the cold coupler part had shown a leak (M3C7).

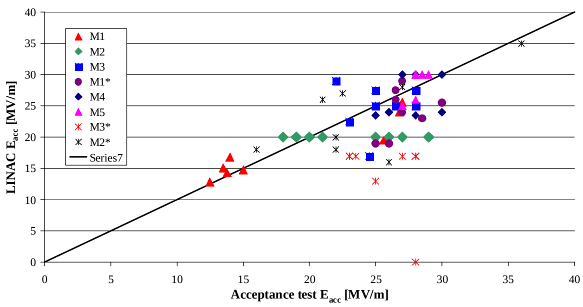

Figure 1: Comparison of the accelerating gradient in the low power acceptance test with the gradient achieved in the machine for each individual cavity.

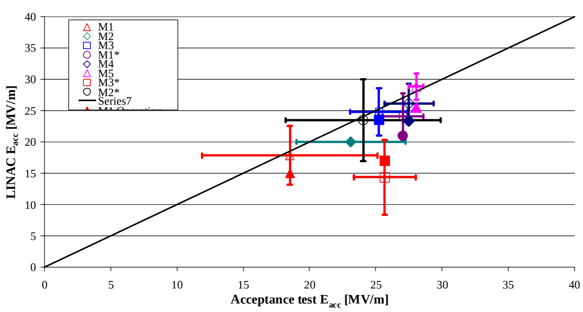

Figure 2: Comparison of the average gradient of the cavities achieved in the acceptance test and in the accelerator (open symbols). The maximum operational gradient of the modules is also shown (full symbols).

- Coupler vacuum to beam vacuum leaks

During the disassembly of on module, a leak was found in one of the coupler ceramics. During operation this was undetected and posed no problem for the machine.

- Helium system to isolation vacuum leaks

Only one module (M3) has shown leaks in the helium system. The vessels of two cavities were found to be leaky even though they were checked for leaks before the module assembly. Another vessel was found to be leaky before installation and was successfully repaired. It turned out, that the welding of the helium vessels was done incorrectly. Better QC measures were introduced. Although cryogenic operation being more difficult the module was operated for more than 2 years.

CRITICAL MECHANICAL ASSEMBLIES

A large variety of issues with different impact on cavity performance occurred in the mechanical assemblies. As an example, a re-assembly of cavity-to-cavity connection is very critical as there is no re-cleaning with high-pressure water rinsing (HPR) possible at this late stage of the assembly process (see below). A less critical assembly would be the assembly of the tuner to the cavity as this has no direct impact on the superconductor's surface.

- Cavity interconnection

The final cleaning of the cavity with a high pressure water rinse takes place after the assembly of the HOM and field pickup antennas and before the assembly of the high power coupler. There is no additional cleaning of the cavity inside surface during the module assembly due to the potential time delay. For the string assembly the cavities have to be carefully vented and the end flanges are disassembled. All parts need to be thoroughly cleaned.

In most cases the first connection was leak tight. Some leaks occurred with re-assembly and a re-venting of the system (M1*C6). During the first assemblies the tooling did not fit and lead to difficulties during cavity inter-connection (M2C1 and M2C2). In one case, the beamline gasket did not fit properly due to a mechanical deformation but was mounted nevertheless (M2*C2).

- Assembly of the power coupler

The coupler antenna is mounted in two steps the cold part is attached in the cleanroom while the warm part can only be assembled after the insertion of the cavities into the cryostat vessel. The cold part is attached to the cavity in the cleanroom to seal the beam vacuum in an early stage of the module assembly. To avoid wetting the coupler ceramics during the HPR process, this takes place after the final cavity cleaning. Again, in most cases this assembly went smoothly without serious problems. Re-assemblies were needed for M1*C7, M4C2, M4C7, M4C8, M5C5. In some cases the pickups at the coupler were found to be leaky after string assembly: M2*C7, M3*C3. The string needed to go back into the cleanroom for re-assembly of the pickup antennas. No new HPR was applied to those cavities.

- Variety of components

For the FLASH modules several improved components were introduced during the time of the project. This includes e.g. improved cavities with a more reliable gasket system and couplers with better RF performance.

The variety of components poses a problem as slightly different assembly procedures and the mix of materials (e.g. gripping screws) led to problems during assembly. In other cases special seals needed to be used to join the cold coupler part with the cavity (M4) or a feedthrough did not match with the tuner assembly, so that the string needed to be transported back to the cleanroom (M1*C1).

- Untested components

One of the main reasons for performance degradation or leaks is that cryomodule components have not been tested before installation. This ranges from the already mentioned pick-up antennas and couplers not being pre-processed before installation (M2) to cavities which have been installed after being subjected to special cleaning procedures (M3*-see below). Tighter QC is mandatory and has been successfully implemented for the recent cryomodules (M4 and M5).

The serious performance degradation of M3* needs more explanation. The leaks in the Helium system of M3 were to be repaired. During the disassembly of the main power couplers an error occurred and an intermediate fixture was not used. The inner conductor of the cold coupler part touched the niobium surface of the cavity leading to some copper abrasion. Six of the cavities were selected to be re-assembled (leaky helium tanks – see above) after a special cleaning procedure. First, the copper was removed with citric acid and the cavities were etched about 5-10 um and subjected to HPR. Only one cavity was tested in the low power acceptance test, but five cavities were assembled without a performance check. The lower performance of M3* indicates that the test of the cavities before the module assembly is a mandatory QC step and must not be omitted.

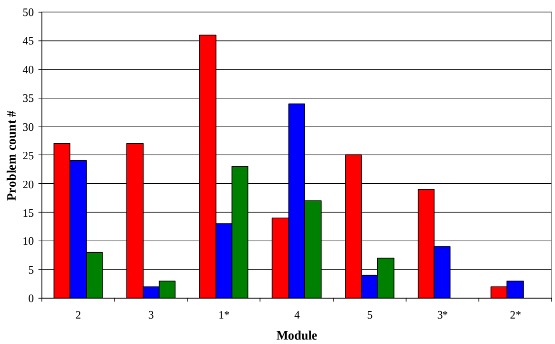

Figure 3: Analysis of assembly protocols. Three categories of problems are shown for each module: Very critical (red), critical (blue) and less critical (green)

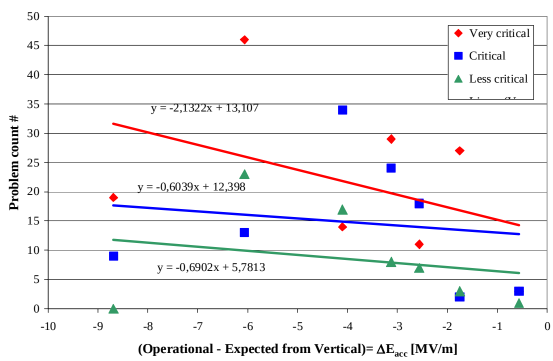

Figure 4: Correlation of the problem count with the difference of the operational gradient of the modules and the average gradient achieved in the acceptance test.

RELATION OF ASSEMBLY PROBLEMS AND CAVITY PERFORMANCE

In an attempt to better quantify the analysis, three categories of problems were introduced (figures 4 and 5).

- Very critical (shown in red colour): e.g. problems related to beam vacuum with a potential contamination of the superconducting niobium surface.
- Critical (blue):e.g. assembly procedures with tight tolerances or incompatible materials (gripping screws etc.) that lead to re-assemblies or repairs
- Less critical (green): e.g. problems leading to time delays like cable shorts etc.

The problem count for each of the categories is shown for each module assembly in figure 3. A clear improvement over time (with the exception of module 3*) is visible due to improved quality control procedures being implemented. Some correlation can be established when plotting the problem count over the difference between the operational gradient of the module in the machine and the expected gradient from the vertical test (figure 4). The 'very critical' problems have clearly the strongest correlation to the lost performance. Nonetheless, the rating into problem categories needs to be refined further. As can be seen in figure 3 for M1* the 'very critical' problems are more than for M3* which contains the untested cavities which certainly have a strong effect.

CONCLUSION

The analysis of the available assembly protocols for the TTF accelerator modules identifies a number of problems which can potentially degrade the cavity performance. With improved quality control measures the number of these problems is reduced as can be shown by the performance of M4 and M5. Both modules meet the specifications for the European XFEL. One important quality control step is the acceptance check of all components assembled into cryomodules. A method to establish a correlation between problem count and gradient degradation has been proposed. Further refinement of the problem analysis is needed to make the correlation stronger. Finally, this method should help to refine quality control procedures further to guarantee the performance of the superconducting accelerator modules.

ACKNOWLEDGMENTS

The author would like to thank the colleagues at DESY for the intense discussions and their help to understand the assembly protocols: R. Lange, K. Jensch, W.-D. Möller, D. Kostin, D. Reschke, A. Matheisen, B.v.d.Horst, M. Schmökel, W. Singer, D. Proch, H. Weise. These people helped significantly with the analysis. The support of the EC Research Infrastructure Activity under the FP6 "Structuring the European Research Area" program (CARE, contract number RII3-CT-2003-506395) is acknowledged.

REFERENCES

[1] "A VUV Free electron Laser at the TESLA Test Facility at DESY – Conceptual Design Report", DESY Print, June 1995, TESLA-FEL 95-03.
[2] R. Brinkmann, et al., editors, TESLA - Technical Design Report, volume II, DESY, March 2001, DESY 2001-011, , TESLA 2001-23.
[3] B. Aune et al. The Superconducting TESLA Cavities. *Phys. Rev. ST-AB*, 3(9), September 2000. 092001.
[4] L. Lilje, P. Schmüser et al., "Achievement of 35 MV/m in the Superconducting Nine-Cell Cavities for TESLA," *Nucl. Inst. Meth. A* **524**(1-3), 1-12 (2004).
[5] L. Lilje, CARE note, to be published