SUPERCONDUCTING ACCELERATING MODULE TESTS AT DESY

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Abstract

The 9-cell TESLA type superconducting cavity based accelerating module is one of the key elements of the successfully operating FLASH linear accelerator at DESY as well as of the XFEL [1], [2], [3]. The next FLASH 1.2 GeV upgrade and new XFEL prototype module has been assembled and tested on Cryo Module Test Bench (CMTB) at DESY [4].

INTRODUCTION

The planned XFEL should provide transverse coherent X-rays at wavelengths down to 1 Å in pulses of 100 fs duration with dark intervals between pulses ranging from nanoseconds up to seconds in a most flexible way. XFEL linear accelerator (LINAC) will have 100 SRF modules providing the electron beam with energy about 17 GeV. One XFEL LINAC module contains 8 TESLA-type SRF cavities (Fig.1).

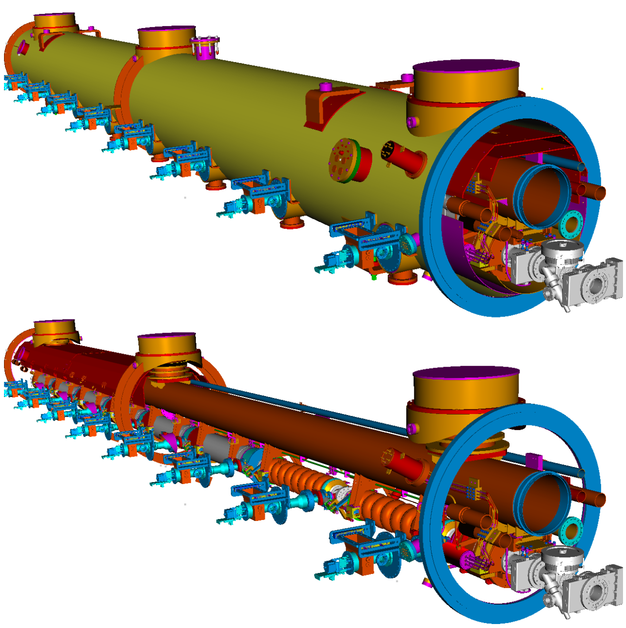

Figure 1: XFEL LINAC SRF module.

The VUV-FEL and XFEL accelerating cavity is a 9-cell standing wave structure of about 1m length whose fundamental TM mode has a frequency of 1300 MHz. It is identical to the so-called TESLA cavity, made from solid niobium, and is bath-cooled by superfluid helium at 2 K. Each cavity is equipped with: a helium tank, a tuning system driven by a stepping motor, a coaxial RF power coupler; a pickup probe, and two higher-order mode (HOM) couplers. The superconducting resonators are fabricated from bulk niobium (Nb) with the highest critical temperature and critical magnetic field of all pure metals (Tc = 9.2 K; superheating field of approx. 240 mT) by electron-beam (EB) welding of deep-drawn half cells. The tubes for the beam pipes and the coupler ports are made by back extrusion and are joined to the cavity by EB welds. Application of the recently highly developed cavity production and treatment techniques combined with an extremely careful handling in a clean-room environment led to acceleration gradients of more than 35 MV/m combined with cavity quality factor Q_0 in range of 10^{10}. The XFEL design gradient of 23.6 MV/m can be achieved reproducibly now. The RF power sources for the XFEL accelerating modules are the 10 MW 1.3 GHz klystrons connected to the modules through the waveguide power distribution system.

First XFEL prototype module PXFEL1 was assembled in team-work with XFEL Cold Linac Partners (IHEP/Beijing, CEA-IRFU/Saclay, IN2P3-LAL/Orsay, INFN/Milano, CIEMAT/Madrid, DESY) at DESY using 3 cavities from disassembled module 8 (assembled and tested before), 5 cavities from the new production and cold-mass from IHEP/China. This module will be used for the FLASH energy upgrade. After the upgrade FLASH LINAC will have 7 accelerating SRF modules to reach 1.2 GeV for the next user run.

CRYO MODULE TEST BENCH

The Cryo Module Test Bench (CMTB) was built at DESY to test the accelerating SRF modules and cavities independently from the FLASH operation. CMTB allows the high and low power RF tests, as well as cryogenic tests to be conducted on one SRF module [4]. Module PXFEL1 was installed and tested at CMTB (Fig.2).

Figure 2: PXFEL1 SRF module on the CMTB.

CAVITIES TESTS RESULTS

Before assembly to the SRF module cavities are being treated and tested. CW test done in the vertical test cryostat without the LHe tank and auxiliaries with cavity fully immersed in the liquid helium. Pulsed high power RF test done in the horizontal cryostat fully equipped with the standard TESLA-TTF auxiliaries, main coupler and both Higher Order Mode (HOM) couplers (Fig.3,4).

Vertical Cryostat Tests

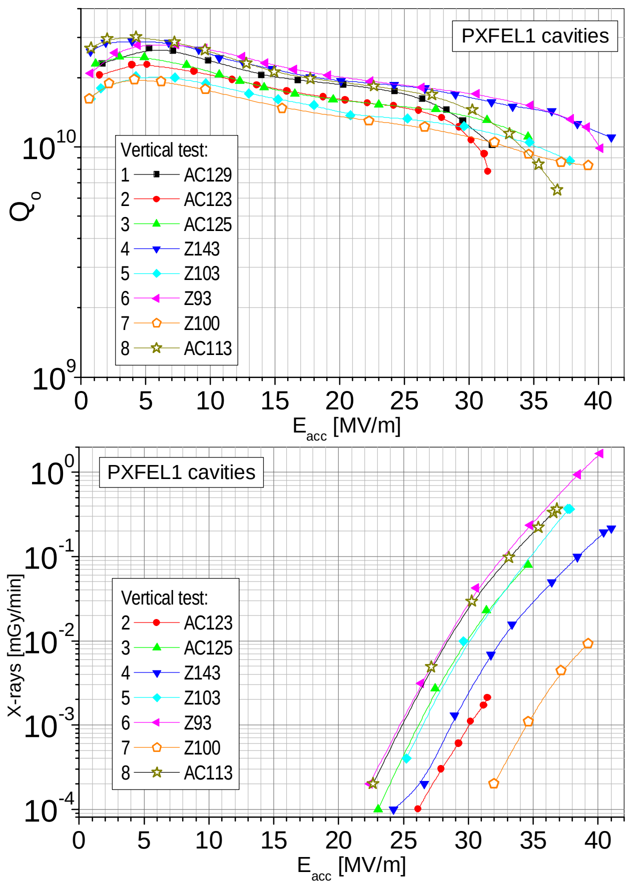

Figure 3: Single cavities CW tests results.

Horizontal Cryostat Tests

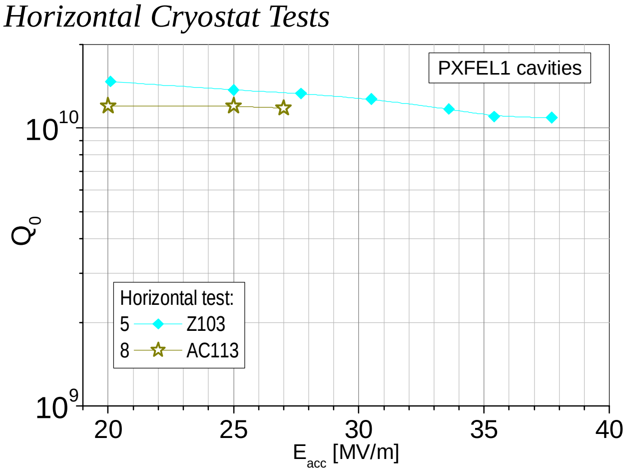

Figure 4: Two single cavities pulsed tests results.

MODULE TESTS RESULTS

RF Couplers Performance

RF power coupler conditioning, done prior to cooling down the module, took about 72 hours. RF power coupler dynamic cryogenic losses (cavities are detuned) are measured, see Table 1. Obtained values are much less, then specified for the XFEL power coupler operation.

Table 1: RF power coupler dynamic losses.

	measured (CMTB)		specification
RF power, kW	120	230	200
4K losses, W	0.1	0.26	0.5
70K losses, W	2.5	3.75	6.0

RF Cavities Performance

The RF power measurements are done using the standard measurement procedure [4]. Module test with equal cavity RF power distribution (Fig.5-8) as well as single cavities tests with only one cavity on resonance at time (Fig.9-11) done. The cavities were tested with the flat-top RF pulse with 0.5 ms rise time and 0.8 ms flat-top. The own quality factors Q_0 measurements were done using the cryogenic losses measurement on the CMTB (Fig.5,7), modules radiation measurements done as well on the both ends of the module (gun / dump side) (Fig.6,8).

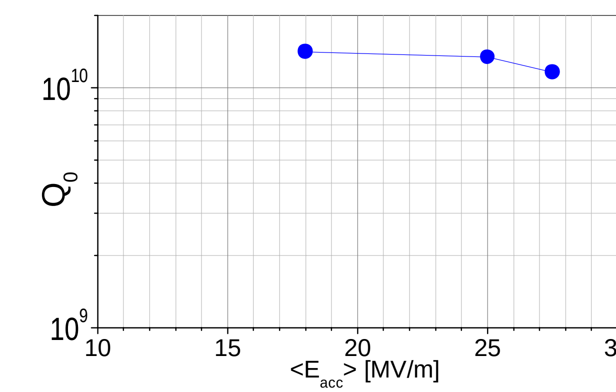

Figure 5: Module test (all cavities): Q_0 vs. E_{acc}.

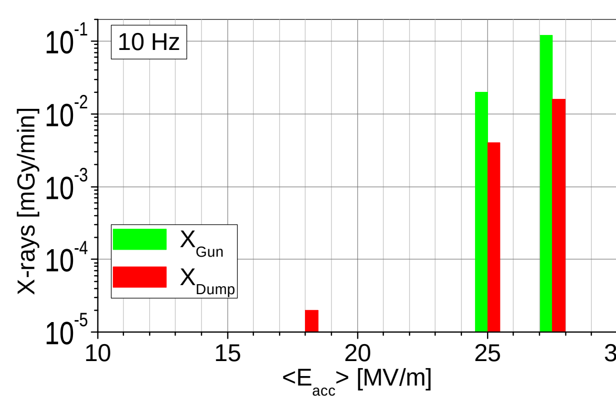

Figure 6: Module test (all cavities): gamma radiation.

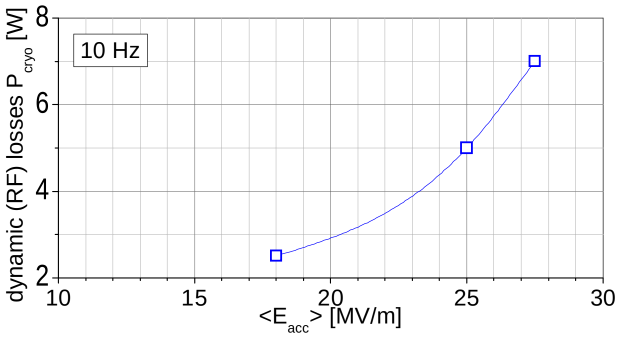

Figure 7: Module test: dynamic cryogenic losses.

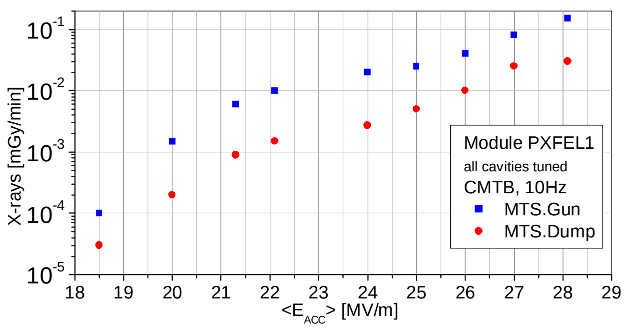

Figure 8: Module test: gamma radiation measured at both module ends (gun / dump) vs. gradient.

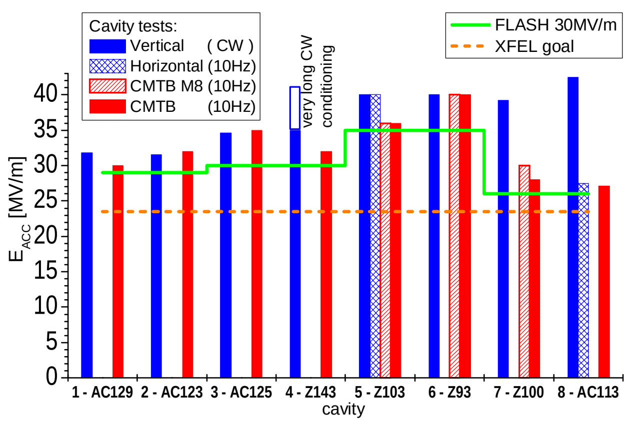

Figure 9: Single cavities test: cavities performance.

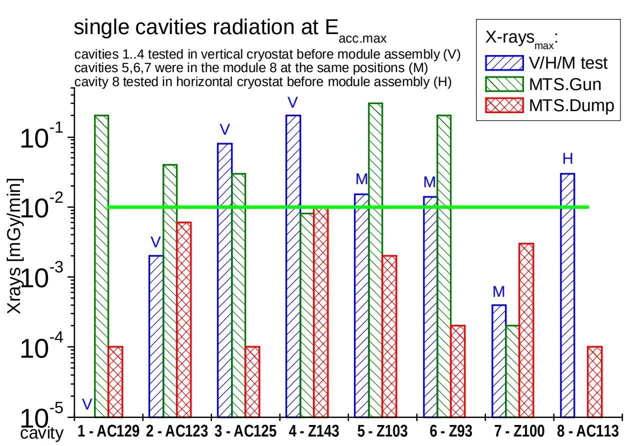

Figure 10: Single cavities test: gamma radiation measured at both module ends (gun / dump).

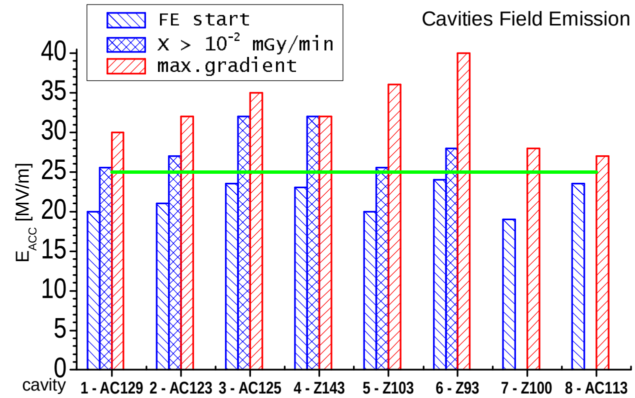

Figure 11: Single cavities test: cavities field emission.

NON-EQUAL RF POWER DISTRIBUTION

To optimize the module performance the tailored non-equal binary RF waveguide power distribution was proposed [5]. This waveguide system connects the RF power couplers in pairs to the klystron through three pre-adjustable nodes so, that the cavities pairs can get different RF power levels, see Fig.12,13. This can increase the usable gradient of the module, compared to the equal RF power distribution. In the fig.9 solid line shows proposed distribution for the PXFEL1 module in FLASH LINAC.

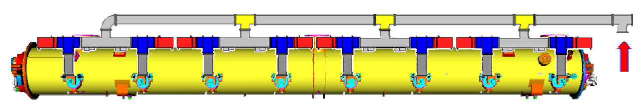

Figure 12: Non-equal binary RF power distribution.

Figure 13: Module PXFEL1 with XFEL-type non-equal pre-adjustable binary RF power distribution.

STATISTICS SIMULATION

XFEL cavities production statistics was simulated using MathCAD software with independent random numbers from a normal distribution with mean μ=27 MV/m and standard deviation σ=5 (from previous cavities production statistics study, D.Reschke [6]), see Fig.14. 32, 64 and 240 cavities storage was calculated with two different study cases:

1) cavities are taken to the module production as soon as 8 of them are ready, see Fig.15;
2) cavities are stored until storage is full, after cavities are sorted by accelerating gradient and used for the modules, see Fig.16.

In all cases cavities are sorted within each module.
Also two different RF power distributions simulated:

1) equal RF power distribution within the module limited by the cavity with lowest accelerating gradient;
2) non-symmetrical binary RF power distribution with cavities sorted and taken by pairs with 4 different limits (cavities 1,3,5,7 from the sorted set).

For the before mentioned study cases total accelerating voltage of the all modules was calculated and compared to the ideal case of all cavities operated at maximum possible gradient as well as to the other cavities distribution case. The total accelerating voltage differences in % for the simulated cases are presented in the Table 2.

For the XFEL we would like to use the non-equal binary RF WG power distribution in order to increase the cavity using factor and thus the available accelerating voltage of the linac. Storing and sorting the cavities without such a RF power distribution, but with equal one (limited by lowest gradient in the module) gives about 20% of total accelerating voltage increase. Using the tailored non-symmetrical binary RF power distribution decreases this difference down to 3 %.

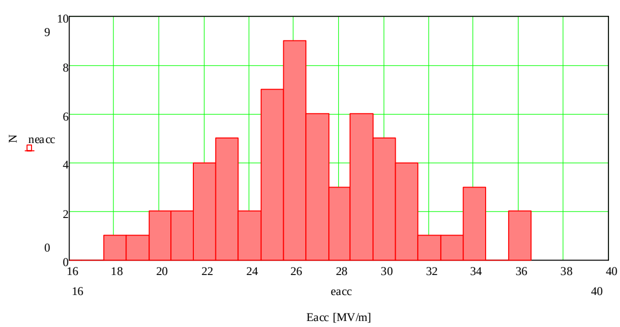

Figure 14: Simulated cavity production of 64 cavities, independent random numbers from a normal distribution with mean μ=27 MV/m and standard deviation σ=5.

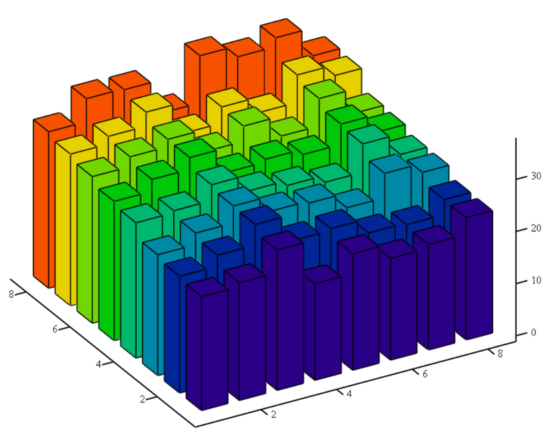

Figure 15: Simulated cavity production of 64 cavities, cavities are not sorted.

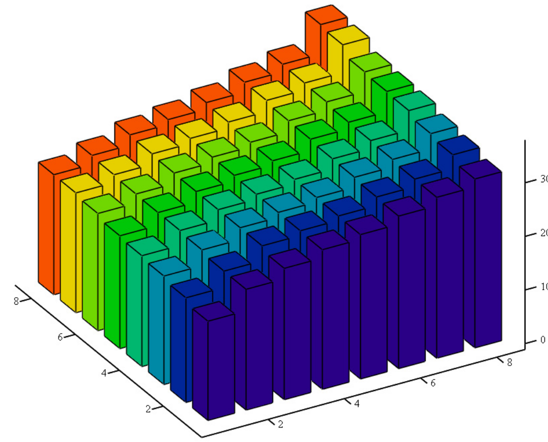

Figure 15: Simulated cavity production of 64 cavities, cavities are sorted.

Table 2: Total accelerating voltage differences.

simulated number of cavities in production	32	64	240
not sorted cavities with equal RF power distribution vs. maximum possible gradient (cavities sum) - absolute accelerating voltage loss	23 %		
not sorted cavities with binary non-equal WG RF power distribution (cavities sorted within module) vs. maximum possible gradient (cavities sum) - absolute accelerating voltage loss	3 %		
sorted (stored) cavities with equal RF power distribution vs. maximum possible gradient (cavities sum) - absolute accelerating voltage loss	6 %	4 %	1 %
sorted (stored) cavities with binary non-equal RF power distribution (cavities sorted within module) vs. maximum possible gradient (cavities sum) - absolute accelerating voltage loss	1.0 %	0.6 %	0.2 %
unsorted cavities vs. sorted (stored) cavities with equal RF power distribution - relative accelerating voltage loss without sorting the cavities	~ 20 %		
unsorted cavities vs. sorted (stored) cavities with binary non-equal RF power distribution (cavities sorted within module) - relative accelerating voltage loss without sorting the cavities	~ 3 %		

SUMMARY

- First XFEL prototype module PXFEL1 was assembled in team-work with XFEL Cold Linac Partners (IHEP/Beijing, CEA-IRFU/Saclay, IN2P3-LAL/Orsay, INFN/Milano, CIEMAT/Madrid, DESY) at DESY using 3 cavities from disassembled module 8, 5 cavities from the new production and cold-mass from IHEP/China.
- Module was successfully tested. Cavities gradients from 27 to 36 MV/m reached, module operation with average gradient of 30 MV/m using tailored RF power distribution is possible.
- Deriving from statistical study, storage and gradient based sorting of the cavities before assembly to the module gives about 20% of total accelerating voltage increase, but if the tailored binary non-equal RF power distribution is used the increase due to the sorting is only 3 %.

ACKNOWLEDGEMENT

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