Continuous Wave Operation of Superconducting Linacs

Summary of Working Group 5

TTC Meeting, KEK, 25-29 September 2006, Tsukuba, Japan

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1. INTRODUCTION

The talks in WG5 covered a small fraction of a broad subject which is continuous wave (cw) or near-cw operation of superconducting linacs. The eleven talks (in the chronological order) were presented by:

1. J. Sekutowicz (JS), "Parameter Set for High Duty Factor and CW Operation of a TTF-like Cryomodule; An Example"
2. B. Petersen (BP), "Some Limitations for the Helium II Cooling of SC Cavities"
3. W. Anders (WA), "CW Tests of TESLA Cavities and RF-sources at the HoBiCaT Test Facility at BESSY"
4. S. Simrock (SS), "LLRF Consideration for CW Operation"
5. A. Matheisen (AM), "Analysis of DESY Cavity Data for CW Operation of Cavities"
6. P. Kneisel (PK), "Choice of Material and Treatment for High Qo at Moderate Gradients"
7. P. Kneisel (PK), "Status of the Pb-Nb SRF-gun"
8. K. Watanabe (KW), "HOM Coupler Issues for the STF-Baseline Cavities at KEK"
9. W.-D. Möller (W-DM), "HOM Couplers Issues for the 3.9 GHz Cavity"
10. N. Solyak (NS), "New Design of HOM Coupler for 3.9 GHz Cavity"
11. I. Campisi (IC), "HOM Coupler Issues at SNS".

Due to a shortage of the allocated time and absence of many experts we could discuss very briefly only several topics we considered as important for future cw or near-cw applications of superconducting acceleration systems, mainly as drivers for photon facilities. It was to us natural to investigate at first modifications we need to do in a TTF-like cryomodule for the operation in the cw or near-cw mode. Three talks were devoted to that topic (BP, WA and JS). In the two following talks authors presented the intrinsic quality factor statistics of the DESY cavities (AM) and discussed a possible approach to reach its high value for bulk niobium cavities (PK). LLRF for the cw operation was discussed in one talk (SS). Also R&D program for a cw-operating electron gun was considered in one presentation (PK). The last topic, HOM coupler issues, was discussed in four presentations by KW, W-DM, NS and IC. This discussion was continued at additional meeting on the next day, September 27th.

2. CW AND NEAR-CW OPERATION OF A TTF-LIKE CRYOMODULE

Parameter Set (JS)

The presented here parameter set for the cw or near-cw operation of a superconducting linac driving a FEL facility has been analyzed and proposed in frame of the EUROFEL[1] studies. While neither a final linac energy nor generated photons energy could be specified in these studies, we proceeded with a "modular approach", presenting parameters for an accelerating unit (Fig.1). Having the operating parameters of the unit one can easily find for a particular project: number of units needed to reach energy spec, required capacity of a cryogenic plant, AC power consumption and other data relevant to the project. The studies have been intended to apply to future light sources and/or to an upgrade of the European XFEL linac. Their implementation should be seen as a long term and far future process. This allows for exploring here not only the existing state-of-the-art technologies but also those being under development (e.g. big grain niobium cavities, 120 kW upgraded IOT transmitter, cw operating SRF gun) which preliminary experimental results are very promising.

The accelerating unit consists of: eight 9-cell Nb cavities housed in one TTF-like cryomodule, a 120 kW IOT amplifier, a driving 760 W amplifier, ~170 kW power supply and the power distribution system.

The static cryogenic losses per cavity in the TTF type cryomodule are: 0.15, 1.0 and 7.5 W at 2, 5-8 and 40-80 K temperature levels respectively. At cw or near-cw operations dynamic losses will be much higher than the static losses, so one has to adjust the length of a RF-pulse (duty factor) to keep the whole cryoplant at a reasonable size. Keeping in mind a possible upgrade of the European XFEL linac, which consists of 116 cryomodules, we assume that for the cw or near-cw operation the upper limit of the cryoplant capacity should not exceed 5 kW at 2K (similar capacity to one cryoplant unit of the TESLA collider or the CEBAF cryoplant). With 30% of that capacity reserved as a safety margin one needs to limit the

[1] Work supported by EU under contract No. 011935 (EUROFEL)

cryogenic load per cryomodule at 2K to about 30 W. The limitation is to some degree arbitrary and for example for linacs which are shorter (have fewer cryomodules) the limiting cryo load per cryomodule can be chosen higher.

The second assumption is that the distribution system dissipates ~3% of the RF power and that maximum available beam power is 77% of the total IOT power. The remaining 20% are reserved for the phase and amplitude stabilization. In addition, we will assume that the bunch charge is 1nC. In reality one can very flexibly change the time separation and charge of bunches keeping constant the average current within the RF-pulse, which length depends only on the cryogenic load. The repetition frequency of RF-pulses is assumed to be 1 Hz.

Table 1 summarizes the parameter set for the cw and near-cw operation resulting from the assumptions. The number of bunches in the energy range 50-200 MeV (5.8 GeV to 23 GeV for 116 units of XFEL type linac, see last row in the table) is shown in Fig. 2. The unit can accelerate up to 1.8 $\cdot 10^6$ bunches at 50 MeV down to 53000 at 200 MeV energy gain. The spacing of the nominal 1 nC bunches varies from 0.54 to 2.42 μs. The RF-pulse length is 1000 ms (real cw) at 50 MeV down to 121 ms at 200 MeV (near-cw regime).

The upgrade of the XFEL linac based on this concept will allow for increased average brilliance by factor of 40 at ~6 GeV and by the factor more than 3 at the nominal energy of 17 GeV.

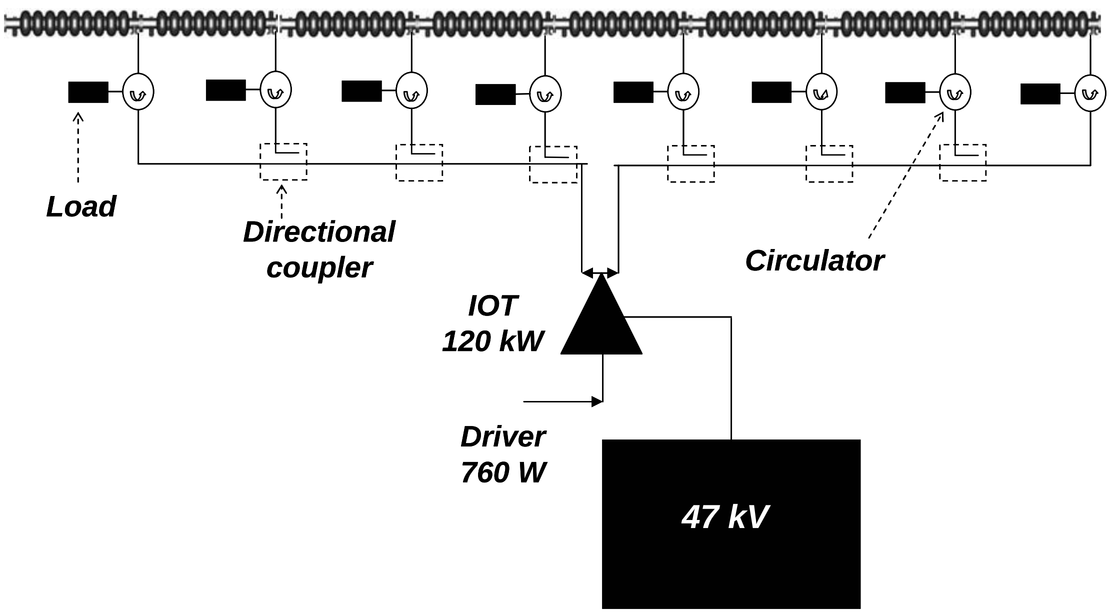


Figure 1: Accelerating unit consisting of: eight 9-cell cavities, 120 kW IOT with symmetric output, a driving amplifier, the power distribution system (eight circulators and loads, six directional couplers) and power supply operating at 47 kV.

Table 1: Parameter set for the Accelerating Unit

Energy gain /Accelerating Unit	[MeV]	50	75	100	125	150	175	200
Eacc	[MV/m]	6.01	9.01	12.02	15.02	18.03	21.03	24.04
Duty Factor	[%]	100	69.4	44.6	29.9	21.2	15.7	12.1
Bunch spacing when charge/bunch = 1nC	[μs]	0.54	0.81	1.08	1.35	1.62	1.89	2.16
Number of 1 nC bunches/s	[10^6]	1.855	0.857	0.412	0.220	0.129	0.081	0.053
Opt. Qext to keep power $\leq$ 14.5 kW/cavity	[10^6]	3.1	6.7	11	14	20	27	36
Max. allowed microphonics peak-peak	[Hz]	34	34	34	34	24	18	14
XFEL Upgrade Energy for 116 acc. units	[GeV]	5.8	8.7	11.6	14.5	17.4	20.3	23.2

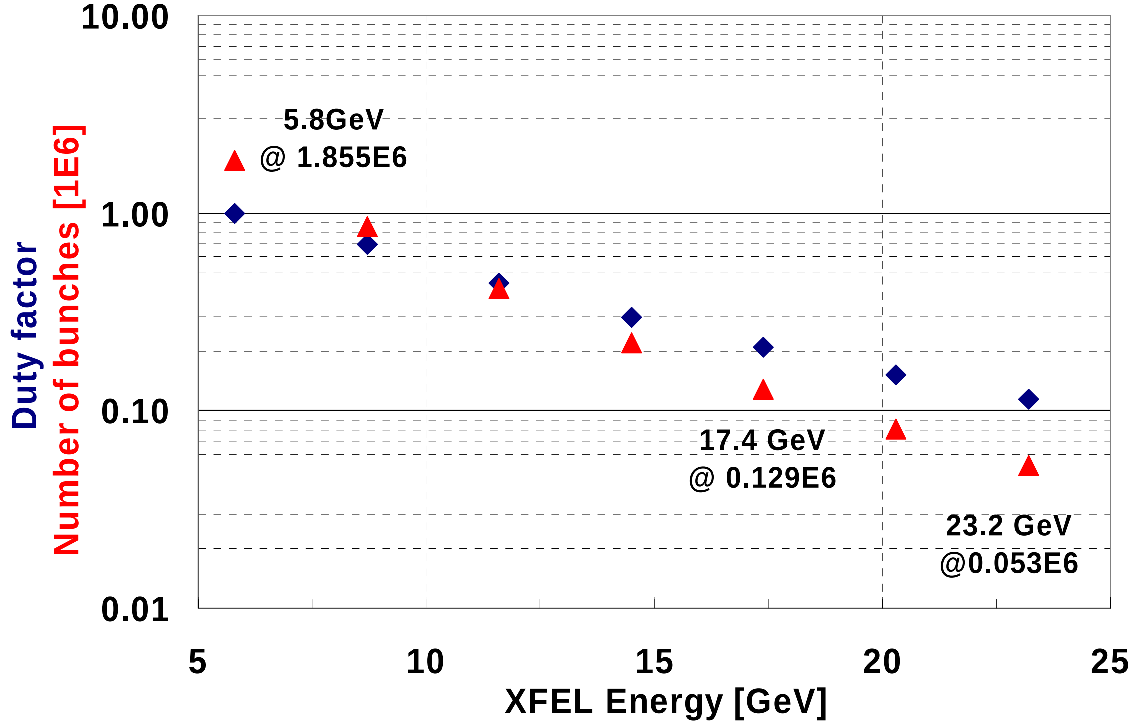


Figure 2: Duty factor (diamonds) and number of 1 nC bunches per second (triangles) for the parameters shown in Table 1.

Limitations in the He II cooling (BP and WA)

The heat load of the TTF cryomodule is limited by the heat transfer in the 76 mm diameter 2-phase tube and the chimneys connecting that tube with the He-vessels of the housed cavities (Fig. 3). The original TTF cryomodule design (see transparencies of WA and BP) allows for about 30 W load per cavity. This was confirmed by the BESSY group and matches very well with the theoretical chimney limitation being a product of its cross-section and the heat transfer capacity of superfluid helium, which is 1.4 W/cm^2. The chimney diameter does not limit the XFEL operation as it is proposed above, but it is by far not sufficient for the BESSY FEL cryomodule with the dynamic loss of about 40W/cavity.

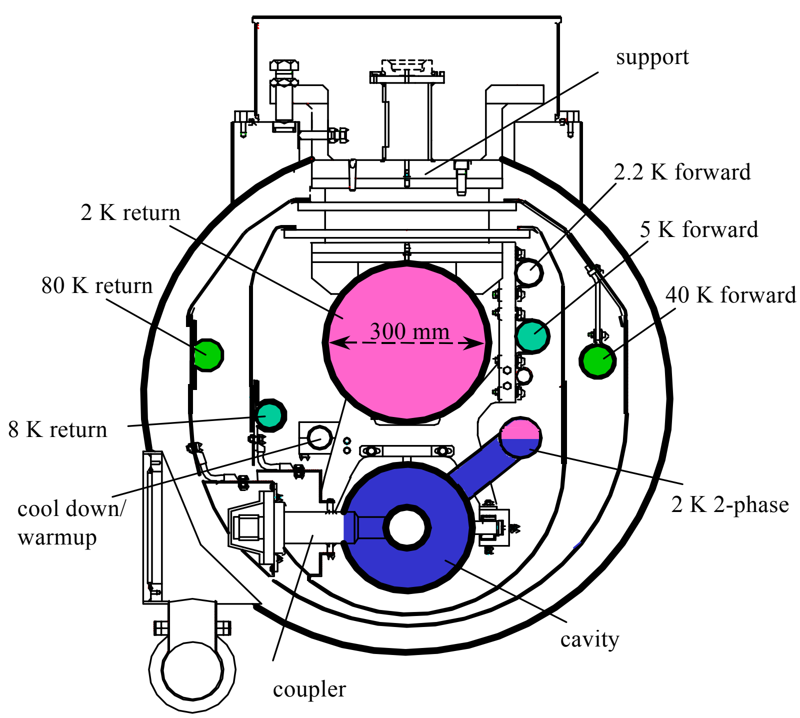


Figure 3: Cross-section of the TTF cryomodule.

The enlarged to 90 mm chimney diameter and 100 mm diameter of 2-phase tube have been proposed for the BESSY cryomodule to ensure the safe operation in the cw mode at 20 MV/m with the total dynamic load of ~300 W per cryomodule. The cryo-limitation for the XFEL operation might result from the length of the so called cryogenic string, being a chain of 10 cryomodules. The total cryo-load of the string, when it will be operated as it is proposed above, will be of the order of 300 W too, so also here an increased diameter of the 2-phase tube is strongly recommended, especially that it has rather minor impact on the capital costs.

Fundamental Power Coupler and HOM Couplers (WA)

The TTF input couplers have been designed for the pulse operation. The couplers were successfully tested up to 1.6 MW peak power at 5 Hz repetition rate of 1.3 ms RF pulses. Without any modification the TTF coupler can handle up to 3.5 kW of the average power. The cw or near-cw operation requires an additional cooling of the inner conductor to keep the temperature stable for the average power higher than 3.5 kW. The TTF-III type coupler with and without the additional cooling was tested at BESSY. The test results are summarized in Fig. 4. With a moderate airflow the coupler was tested up to 10 kW of the average power showing a marginal temperature rise. An extrapolation of that result with the proportionally increased airflow shows that the operation at 25 kW is technically possible. Further experiments with more average power will follow in the near future.

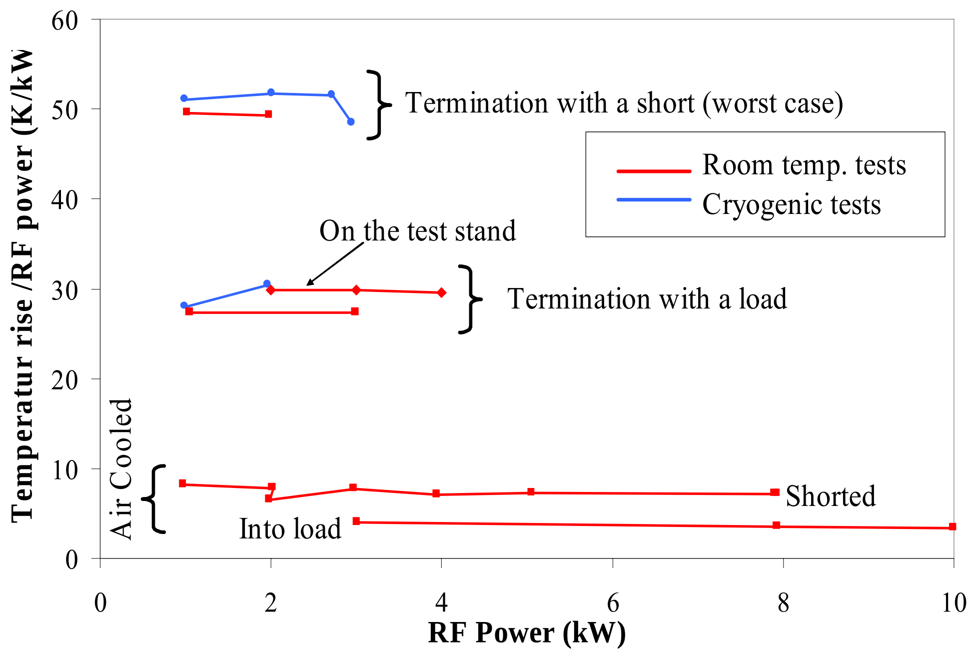


Figure 4: Temperature rise of the sensor in the inner conductor per kW of the applied average power. All tests were performed in HoBiCaT except the one marked "on the test stand".

Alike the input TTF coupler, HOM couplers were designed for a low duty factor operation. They are attached outside the helium vessel for the cost and assembly simplification reason. The location causes very limited cooling of their output antennae, which for an increased duty factor at higher gradients easy become normal conducting and hence dissipate substantial amount of the stored energy into 2 K environment. Much effort was made in the past several years to develop a feedthrough with an enhanced heat conduction to keep the antennae in the superconducting state. The R&D program at TJNAF led to the recently commercialized version of the feedthrough, based on sapphire windows embedded in the copper slab enhancing the heat transfer from the superconducting antennae. Two prototypes have been attached to the TESLA 9-cell cavity at DESY, The cavity was shipped to and tested at BESSY. The cw operation at 20 MV/m was very stable and with only small temperature rise in the outputs. The second cold test is in progress, but already that result is very promising, especially for the XFEL upgrade.

Microphonics (WA)

The microphonics of the TESLA cavity was tested in the HoBiCaT cryostat. The result of the test is shown in Figure 5. When the feedback loop was on, acting on the piezo of the cold tuner, the observed microphonics was 2.7 Hz peak-peak. Without the feedback loop 12.3 Hz peak-peak microphonics was measured. That very effective suppression of the frequency modulation will be very helpful for the presented above cw and near-cw operations, especially for high gradients when the loaded quality factor is close to $4 \cdot 10^7$.

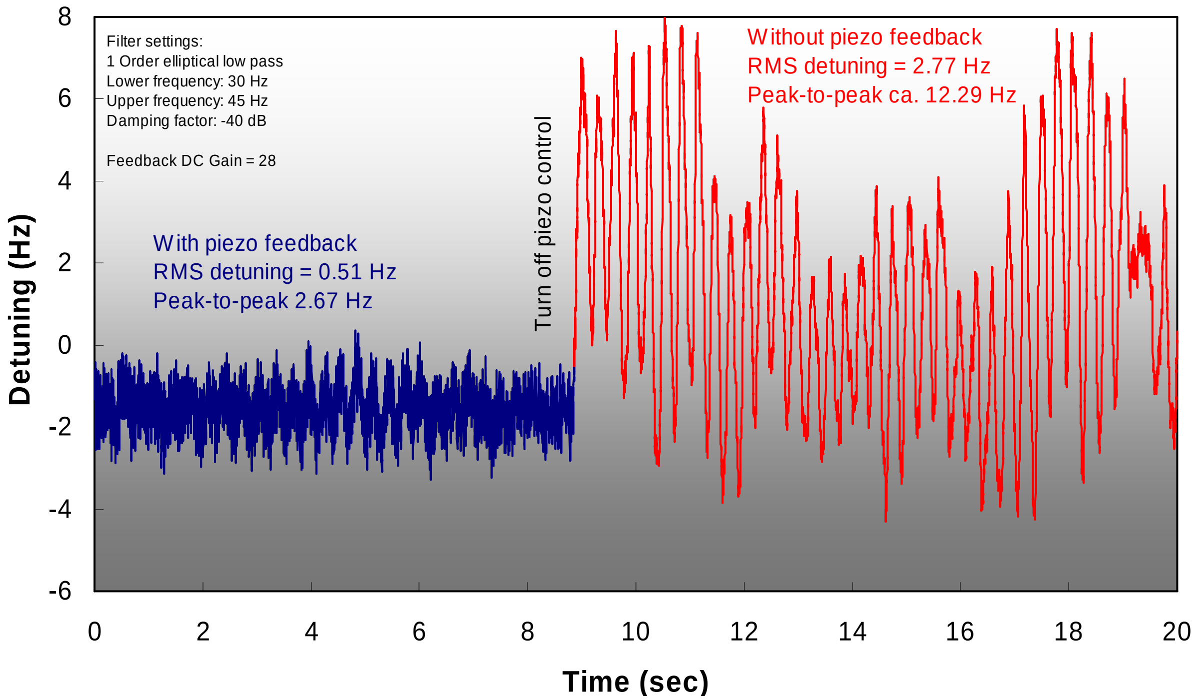


Figure 5: Microphonics test performed in HoBiCaT, with and without feedback loop.

LLRF for High Duty Factor Operation (SS)

The summary of potential advantages and disadvantages for the LLRF control system coming from the cw or near-cw operations are as follows:

Advantages

- Improved field regulation
- Transient perturbations not present
- Low frequencies can be suppressed with very high feedback gain (=> excellent offset suppression)

Disadvantages

- High loaded Q => larger amplitude and phase errors
- Continuous control and monitoring requires different concept
- Potential problem with ponderomotive instability

The experiment at TJNAF with cw operated 1.5 GHz cavity, showed that even at high loaded quality factors ($\sim 10^7$), it is still possible to stabilize amplitudes and phases to a very high degree. Table 2 displays the result of the test.

Table 2: Parameter set for the Accelerating Unit

Range [Hz]	Amplitude Error	Phase Error [°]
$0 - 10^0$	5.5×10^{-6}	1.1×10^{-3}
$0 - 10^1$	1.1×10^{-5}	1.2×10^{-3}
$0 - 10^2$	3.5×10^{-5}	3.0×10^{-3}

3. INTRINSIC LOSSES

After several years of many R&D programs worldwide dedicated to high gradients in superconducting cavities, mainly for the linear collider application reason, we will need now to look in the near future more closely to materials and surface cleaning methods leading to higher intrinsic quality factors. This should be our "technological" goal allowing for the reduction of capital and operation costs of cryogenic plants, which in the case of increased duty factors are a substantial fraction of the whole cost of an accelerator.

Statistics of the TTF structures (AM)

The presented statistics of the TTF cavities at DESY (Fig. 6) shows that on average for the polycrystalline niobium the EP treatment gives higher Q than BCP. Also high Q can be achieved with the hybrid treatment when few microns BCP is done after the regular EP treatment (EP+). The most promising future option seems to be the large grain (LG) niobium treated with the standard BCP. This combination gives very good results, but statistics for these cavities is still rather low. For all kind of treatments the field emission phenomenon (FE) plays an important role in the Q degradation at high gradients and should be mitigated with a proper assembly.

As it is displayed in Fig. 7 a thick layer must be removed from the superconducting surface of the polycrystal niobium to reach good performance. The showed comparison is done at 10 MV/m to eliminate influence of FE. The total removal is especially large for the EP treatment, which since 1997 is being implemented to the TTF cavities and tested extensively with a hope to reach the TESLA (now ILC) spec more repeatable.

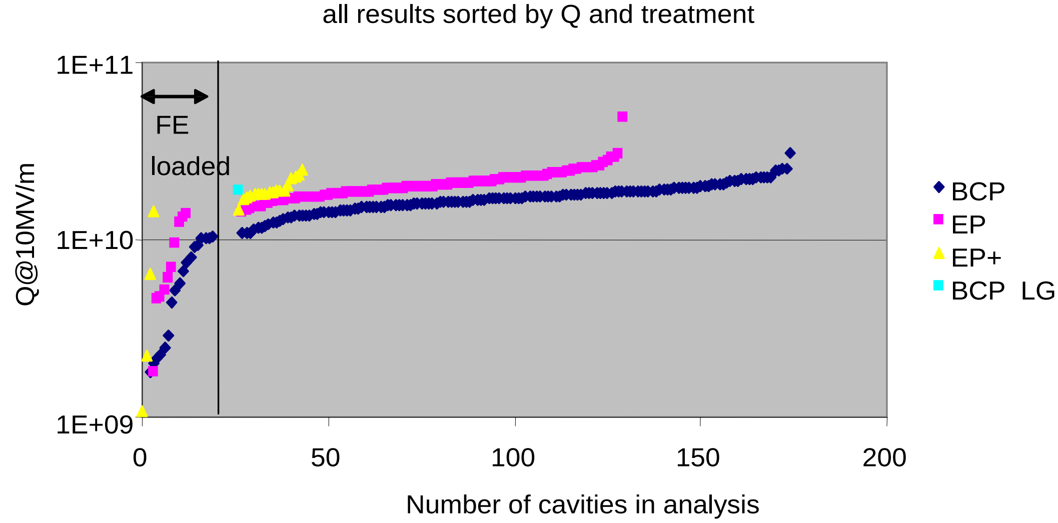


Figure 6: Intrinsic quality factor statistics of the TTF structures at DESY

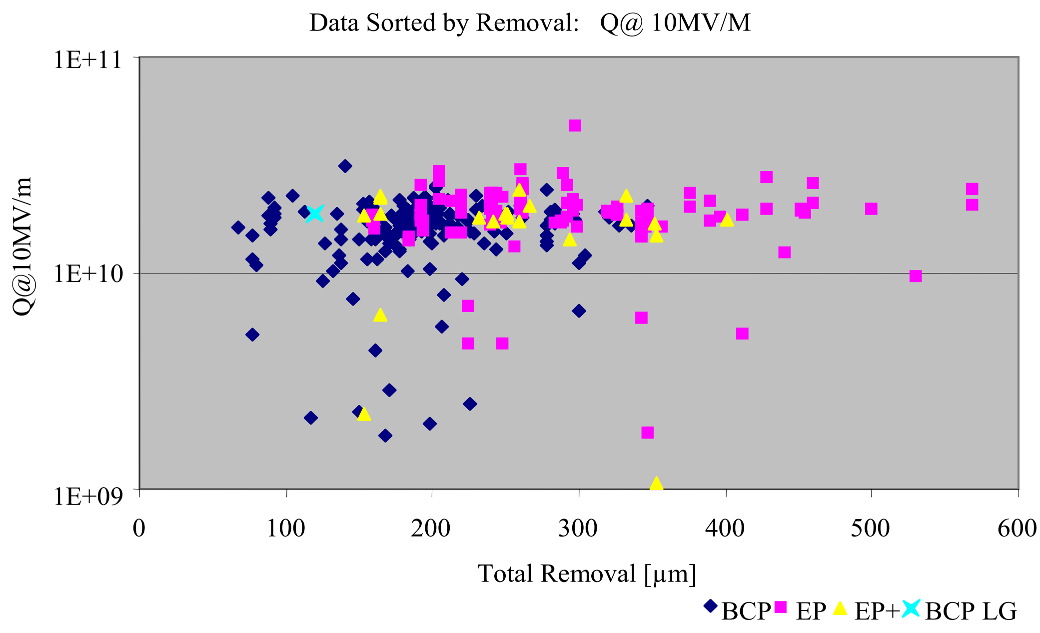


Figure 7: Intrinsic quality factor statistics of the TTF structures at DESY sorted by the total removal.

Single Crystal Niobium Testes at TJNAF (PK)

The breakthrough in the cost saving is expected to come from the very recently proposed (TJNAF group) implementation of the LG niobium. Slices for deep drawing were cut directly from the ingot to build several single-cell cavities at higher frequency. The surface of LG niobium (and single crystal SC niobium) samples showed a very small roughness, below 30 nm, though only the standard BCP treatment has been applied. The very smooth surface together with less grain boundaries could potentially lead to a reduction of the residual resistance. Investigations of a SC niobium 1.3 GHz TESLA cavity fabricated at DESY are continuing at TJNAF to find minimum thickness of the total removed layer (minimum BCP) which provides high gradient and high quality factor. The preliminary, but very promising result obtained at TJNAF is shown in Fig. 8. The cavity was tested at 2K after 80 µm and then at 1.8 and 2 K after the 112 µm layer in total was removed by the standard 1:1:2 BCP treatment. Both the gradient of 35.7 MV/m and Q_0=10^{10} are very impressive and fulfill new spec of the ILC accelerator and by far the spec for the European XFEL.

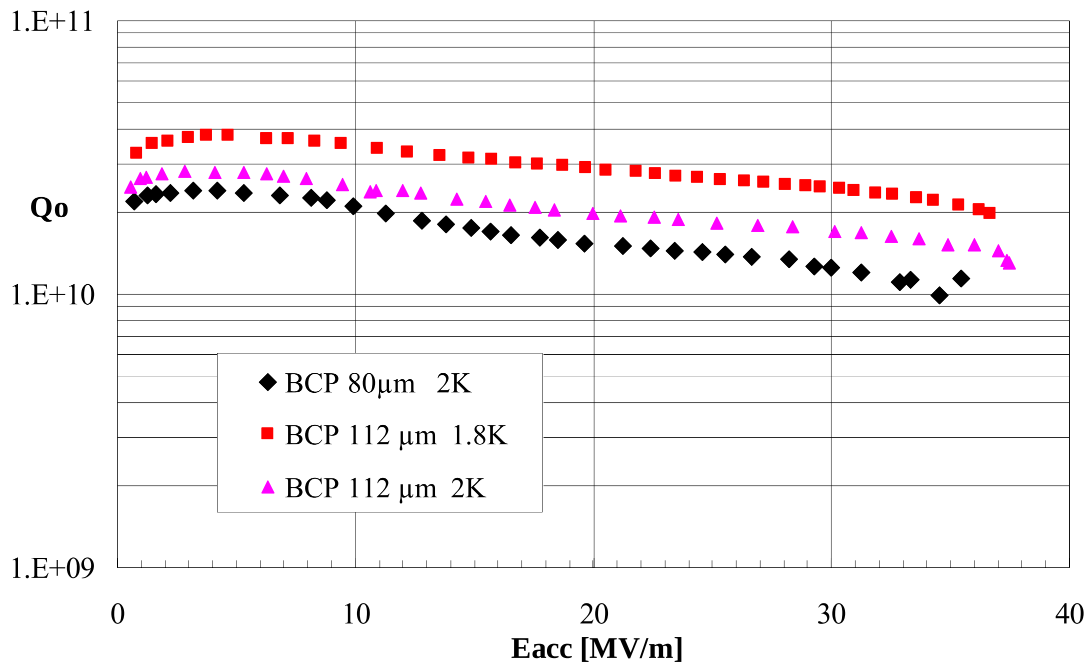


Figure 8: Test results at TJNAF of the single-crystal single-cell cavity fabricated at DESY.

4. STATUS OF THE Pb-Nb SRF-GUN *(PK)*

The cw and near-cw operation of linacs driving FEL facilities requires a cw operating electron sources. One of the possible approaches to 1 mA class electron source is to use a SRF-gun with a superconducting cathode, which is easer to integrate into sc cavity as it compares to standard cathodes (CsTe). Two types of half-cell cavities have been manufactured at TJNAF and DESY to test their RF-performance with the integrated Pb emitting spot. The TJNAF cavity (Fig. 8) has the exchangeable plug which can be coated with any emitting superconductor. The very good performance of that cavity was measured after this Workshop (Fig. 8).

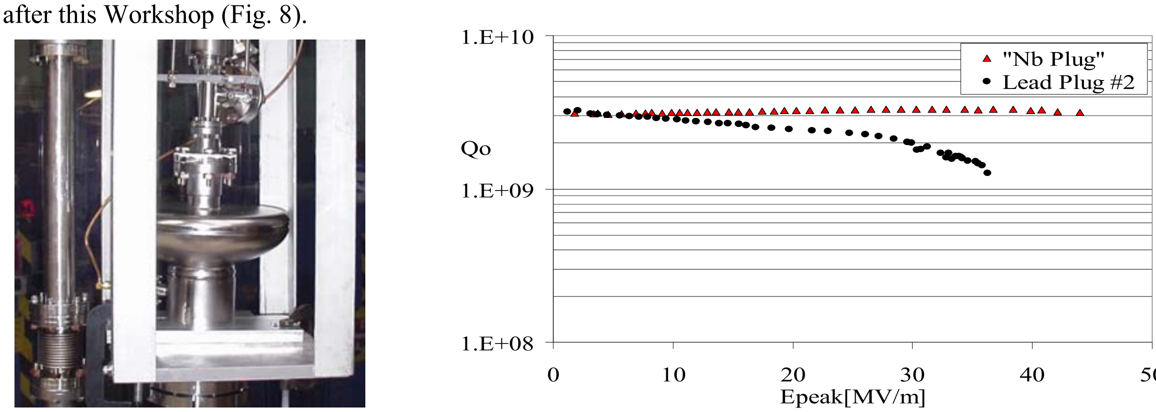


Figure 8: The half-cell cavity with plug. Test results with and without the lead coating.

Also the DESY cavity which has the lead spot direct deposited on the back wall was tested right after the Workshop (Fig. 9).

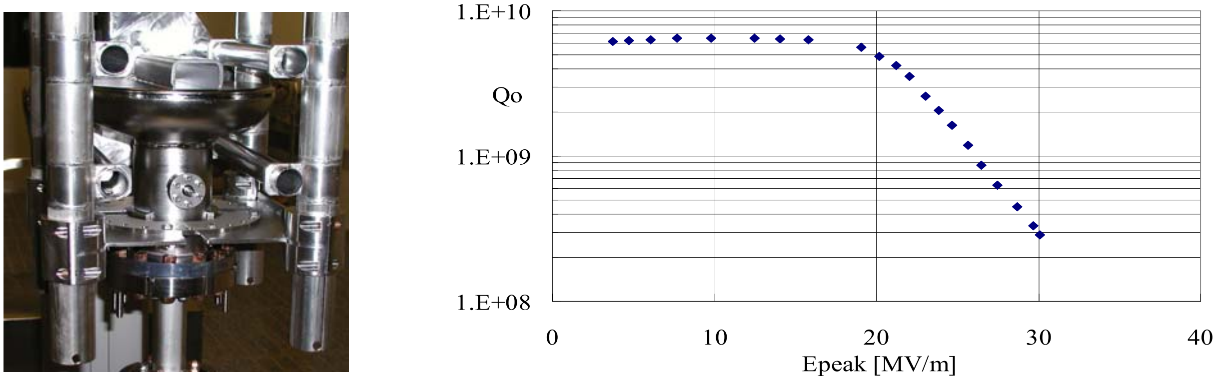


Figure 9: The half-cell cavity with the lead spot deposited on the back wall and its test result with the lead coating.

For both cavities results achieved before the Workshop can be found in the talk by P. Kneisel. Both cavities need further R&D effort leading to higher gradients and higher intrinsic quality factors. In parallel to further RF tests the Pb quantum efficiency measurement at 2 K is under preparation at TJNAF with contribution and support from the BNL group.

5. HIGHER ORDER MODE COUPLER ISSUES

Scaling, modifying, cw operation and selection of components for the TESLA HOM coupler is not an easy task. It should be our highest priority to understand all phenomena we observed in the testing (FERMI, BESSY, Rossendorf, KEK and TJNAF) and operation (SNS) of the HOM couplers. One can draw already now the first conclusion that for all high duty factor applications the high heat conductance feedthrough must be applied to keep output antennae superconducting at any operating gradient. Fortunately, such a feedthrough is available now as it was discussed above (*WA*).

HOM Coupler Issues for the STF-Baseline Cavities at KEK (KW)

KEK proposes two shorter (the reason is increased to 84 mm diameter of the beam tubes) versions of the TESLA HOM coupler. The couplers have different F-parts (Fig. 10a) and hence slightly different transfer functions with the 2nd notch located at 4.5 GHz (L-type coupler) and at 4.1 GHz (I-type coupler). Both couplers have been tested and showed several multipacting levels below 16 MV/m (peak field in the end cells), which all could be processed. The couplers have been tested with two types of the output antennae (Fig. 10b). The heating was observed for both applied types. The temperature rose at 14 MV/m and 32 MV/m for the regular antenna and for the short antenna respectively. The result obtained for the regular probe agrees well with the result of the cw test in the vertical cryostat which was conducted at DESY in 2004, when the same kind of the commercial feedthroughs were used for the outputs of the TESLA HOM couplers.

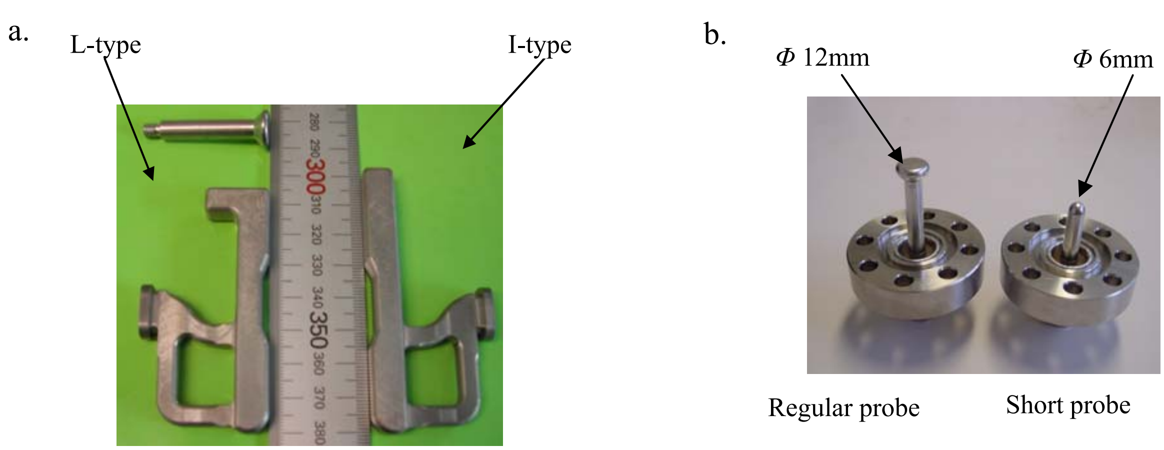


Figure 10: a) Two different F-parts, b) The regular and shorter output antennae (probes).

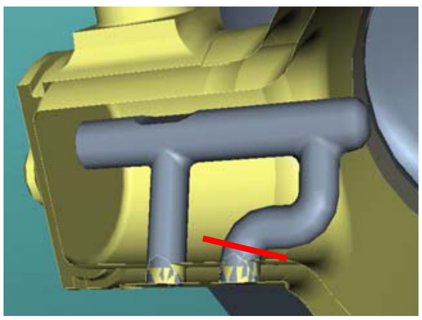
HOM Couplers Issues for the 3.9 GHz Cavity (W-DM)

The HOM coupler for third- harmonic 3.9 GHz cavities has been based on the TESLA HOM coupler design. Two 3.9 GHz couplers have been tested with 9-cell cavity. The following observations have been made in series of the performed tests:

1. Q/T, Rs improved after first Q/E in Pi and 0 mode
2. Q/E, Q improvement with high power (processing with pulses)
3. Multipacting observed
4. 8-11 MV/m Eacc reached in pulsed regime. No quench, power limitation due to low Q.

The computer modelling confirmed the observed multipacting phenomenon at the first bend inductance, close to its welding to the can (Fig. 11a). Loop inductances in both couplers were broken during the tests (Fig. 11b). This indicates enormous heating at both bended inductances and dissipation of the whole supplied power at these locations. The computed stress at the bending for 50 W dissipation seems to be high enough (112 MPa) to crack the inductance which diameter is 4 mm only. The explanation is that the multipacting process makes both locations normal-conducting and then the whole power (up to 100W) is dissipated in the inductances.

a.



b.

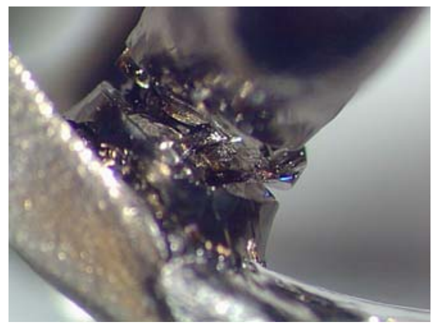


Figure 11: a) Cross-section of the 3.9 GHz HOM coupler. The multipacting location is marked with red line. b) Photograph of the broken inductance.

New Design of HOM Coupler for 3.9 GHz Cavity (NS)

Several new HOM couplers were proposed to replace the first version of the 3.9 GHz HOM coupler which performance was reported above. The strategy for new designs is as follows:

- Increase of MP threshold by ~10 times
  - Increase frequency gap between HOM internal resonance and notch frequency
  - Increase notch gap 0.6mm→~2.5mm and gap between bended leg to wall of the can to shift up MP level
  - Make gap geometry rounded to reduce MP

- Increase thickness of the F-part 4mm→6mm
  - Same welding technique as DESY to escape large grains in F-part body/basement
  - Improve thermal conductivity and mechanical properties

The so called "2-post" new design seems to be the best candidate to replace the first version. The new coupler model is shown in Fig. 12. It maintains sufficient HOM suppression, has no MP levels below 20 MV/m and has much better heat

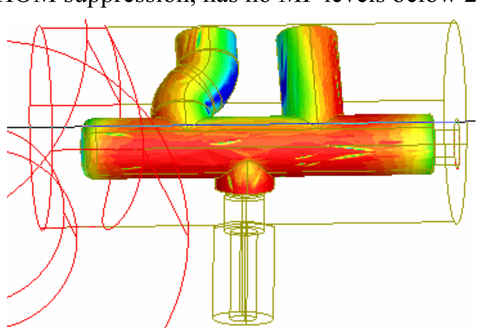


Figure 12: The new design of 2-post HOM coupler as proposed at FNAL.

conduction due to the increased 6 mm diameter of the F-part. The transfer functions of the original HOM coupler (blue line), new 2-post coupler (red line) and three other versions being under consideration are displayed in Fig. 13.

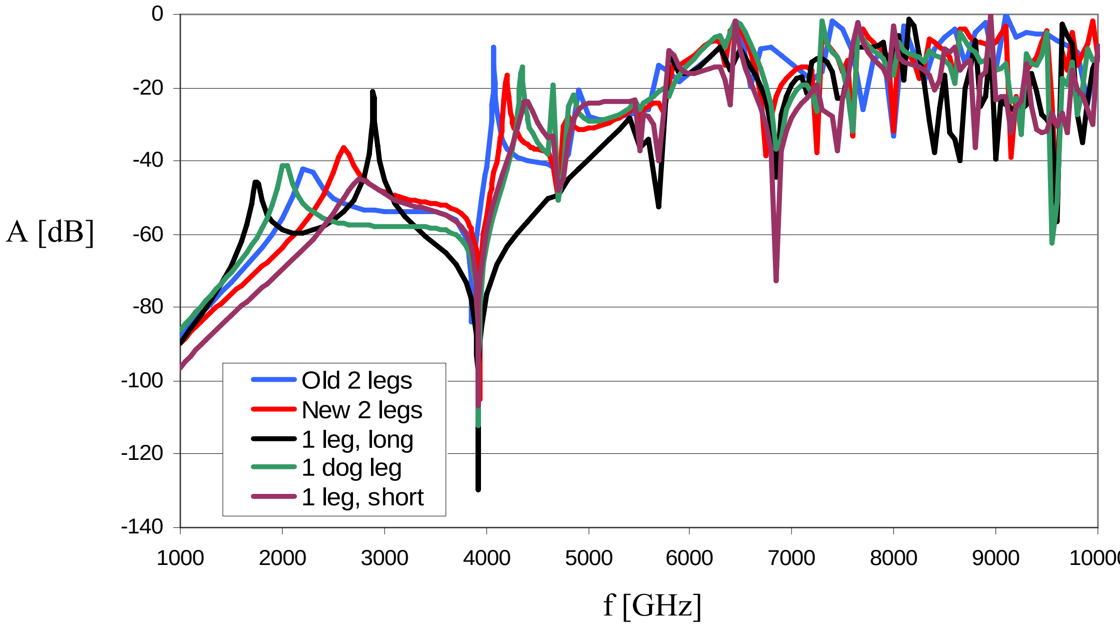


Figure 13: Transfer functions of the HOM couplers for 3.9 GHz cavity.

HOM Coupler Issues at SNS (IC)

The commissioning of the SNS linac showed several issues related to the improper performance of some HOM couplers:

- 2 cavities are not in service
- About 10 cavities show abnormal fundamental frequency signals through HOM couplers
- Electron activity around HOM coupler seems to be the main cause along with well-known thermal issues
- These cavities are running at reduced gradients and/or lower rep. rate pending further investigations
- Cross talk among channels sampled via HOM ports is observed
- Almost all inline attenuators in the HOM ports have been damaged/modified, possibly by excessive bursts of power
- Interlocks on HOM have been difficult to implement due to cross talk in many cavities and especially with beam

The location of the SNS HOM couplers and the cross-section are shown in Fig.14.

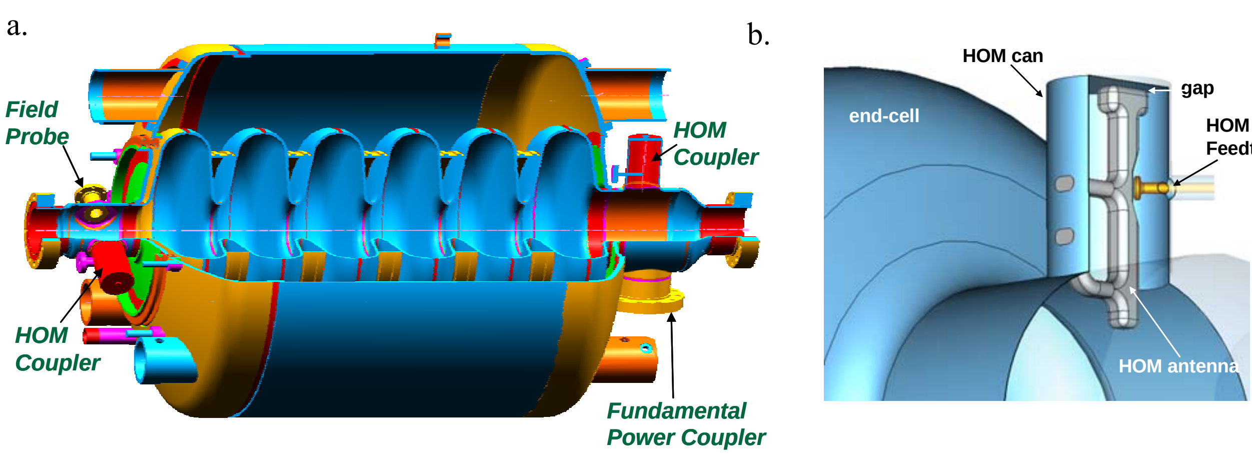


Figure 14: a) SNS cavity with two HOM couplers. b) Cross-section of the SNS HOM coupler.

The antenna heating in these couplers could be expected due to very poor heat conduction of the used feedthroughs. This might lead to deviations in the amount of out-coupled FM power hence the FM filters could be detuned by the dissipated heat. Other phenomena need still more investigation, especially those associated with discharges causing electron activity in the HOM coupler region, especially on the FM coupler side.