CW ADAPTATION OF TESLA TECHNOLOGY IN HoBiCaT *

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Abstract

The HoBiCaT facility has been has been set-up and operated at the Helmholtz-Zentrum-Berlin and BESSY since 2005. Its purpose is testing superconducting cavities horizontally in CW mode of operation and it was successfully demonstrated, that TESLA pulsed technology can be used for CW mode of operation with only minor changes. A specific topic is addressed in this paper: elevated dynamic thermal losses in the cavity walls due to trapped magnetic flux.

INTRODUCTION

Superconducting radio frequency technology has been employed extensively for electron accelerators. However, it is primarily used in a "few cavity"-configuration in storage rings with heavy beam loading, for example the Canadian Light Source, Taiwan Light Source, or DIAMOND, or in a linac configuration with moderate gradient, like CEBAF, or in pulsed operation such as FLASH or XFEL. With the advent of next generation light sources, FELs & ERLs, the push is to develop high gradient (20 MV/m) CW systems for GeV class machines.

The SRF technology of choice, at present time is TESLA [1, 2] which was originally developed for the international linear collider project. With the ILC baseline design calling for two 500 GeV linacs, TESLA was originally designed for highest possible gradients in excess of 30 MV/m, which was only achievable in pulsed operation for cryogenic reasons. Therefore, TESLA has been optimized for pulsed operation.

When aiming at true CW operation, as required for the CW Linacs such as in B*ERL*inPro [3], the Cornell ERL [4], or the CompactERL [5] at KEK new issues arise and certain changes are necessary.

CW-operation entails several drawbacks: First, in order to keep power requirements on the RF amplifiers low, the power coupling antenna needs to be operated at a low bandwidth of several tens of Hertz instead of hundreds of Hertz like in pulsed machines. This is achieved by moving the antenna tip away from the cavity axis. At such a low bandwidth, the shifting of the resonance frequency by mechanical cavity oscillations (microphonic detuning) becomes the major disturbance of the standing RF-wave inside the cavity: If the cavity resonance frequency moves too far away from the 1.3 GHz operating frequency, incoming RF-power is reflected at the input power coupler instead of coupling into the RF-field. In order to ensure a constant field level under these conditions, excess RF-power needs to be made available by the RF-amplifiers which increases the total cost for the RF-system.

Another issue to cope with in CW systems is the larger average cryogenic power as compared to pulsed systems. The heat-load from the full duty cycle is being deposited in the cavities and has to be removed by the cryogenic system. Dissipative losses are due to a finite BCS-surface resistance and increase with the square of the CW field gradient in each cavity. For a fixed linac energy, the cryo-load is minimized by using low gradients. This competes with the increasing linac cost. A cost minimization yields typical values between 15-20 MV/m[6, 7].

Therefore, in CW systems achieving a low RF-surface resistance or high Q_0 is of even higher importance than a high accelerating gradient. Desired values are Q_0-factors ideally much greater than 2×10^{10} at the respective operational field gradient.

THE HOBICAT FACILITY

HoBiCaT (Horizontal Bi-Cavity Test Facility), see Fig. 1, has been designed for testing two multicell superconducting cavities (e.g. TESLA) horizontally and simultaneously under accelerator-like conditions: Cavities can be fully equipped with input power-couplers, pick-up probes, HOM-notch pickups, tuners and magnetic shields.

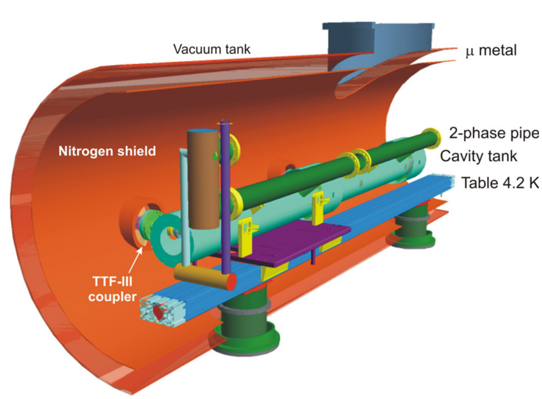

Figure 1: The HoBiCaT facility, photograph of the cryostat and schematic view

The inner wall of the vessel is clad with cryoperm opti-

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mized for room temperature. A cylindrical copper sheet of 1.1 m diameter is mounted inside the vessel, serving as an 80 K intercept. It is cooled with liquid nitrogen at 40 ℓ/h. This copper layer is wrapped in superinsulation foil.

Inside the cryostat, a 3.5 m long, horizontally mounted, hollow, extruded aluminum profile with a flat top and two longitudinal grooves serves as mechanical support for a cavity carriage that slides along the grooves. The cavities inside their Helium tanks are mounted on this carriage. The profile's hollow interior is filled with liquid Helium at atmospheric pressure.

The default operation temperature has been chosen to 1.8 K [8] which corresponds to 16 mbar Helium pressure. At 1.8 K a maximum Helium flow of 4.5 g/s can be reached. This enables the removal of 90 W dissipative power from the cavity. The static losses of the cryostat for two-cavity operation have been determined to 5-7 W.

Q_0 MEASUREMENTS

The cavity field is established by generating a low-level 1.3 GHz RF with a master oscillator (VCO), amplifying it with a 17 kW IOT-based transmitter or a 400 W solid-state-amplifier and coupling it into the cavity through a modified TTF-III [9, 10] coupler via coaxial and rectangular waveguides. A circulator is included into the waveguide path; it prevents reflected power from returning to the amplifier by redirecting it into a 20 kW load.

The coupling strength to the cavity — or external quality factor Q_{ext} — can be adjusted by moving the tip of the coupler antenna in and out or with a three-stub-tuner that is included into the waveguide path between circulator and coupler. The maximum Q_{ext} values can be increased by adding a spacer into the cold part of the antenna mount which gives an offset distance to the antenna tip position from the cavity axis. Since coupling of pickup antenna and HOMs can be neglected compared to the input coupler, the total loaded quality factor Q_L is almost identical to Q_{ext}. Achievable values of Q_L range from 10^6 up to one half of the intrinsic Q_0, approximately 10^{10}. Typical values of choice for Q_L are $3{\times}10^7$ (the destination value for the BESSY-FEL, [6]) or lower for open loop measurements, e.g. microphonics, and as high as possible for closed loop measurements. The most precise results for Q_0 measurements are achieved at critical coupling where $Q_L = Q_0/2$.

For closed loop measurements, the operating bandwidth is of the same order of magnitude as microphonic fluctuations and the cavity field needs to be maintained with a phase-locked-loop. Besides the electronic measurement Q_0 is gained via the Helium flow which is a measure for the dissipative losses: A helium exhaust flow of 1 g/s corresponds to the removal of 20 Watts of dissipated power. The field gradient can be verified by comparing it with the static Lorentz-force detuning which is given by $\Delta f = L \cdot E_{acc}^2$ with $L = -1.0 ... -1.2\, Hz/(MV/m)^2$.

Three-stub-tuner

Using the three-stub-tuner, as depicted in Fig. 2, allows to operate the cavity at minimum reflected power. However, the power budget is prone to errors: Depending on the three-stub-tuner settings, a significant fraction P_{match} of the amplifier power P_{forw} may be dissipated in the resonant matching network between input coupler and circulator, not showing up as reflected power in the first place despite not entering the cavity either. The true forward power delivered into the cavity is different from the amplifier power. With $P_{refl} = 0$ and neglecting cable attenuations we arrive at $P_{cav} = P_{forw} - P_{match}$.

P_{match} is experimentally obtained by measuring the reflected power ON resonance, $P_{refl}(f)$, and slightly OFF resonance, $P_{refl}(f + \Delta f)$ with an adequate choice of Δf of several bandwidths. Due to the high bandwidth of the normal conducting matching network it is safe to assume that $P_{match}(f) = P_{match}(f + \Delta f)$. Detuning the master oscillator by Δf will stop power from entering the cavity, thus $P_{cav}(f + \Delta f) = 0$ and $P_{forw}(f + \Delta f) = P_{match} + P_{refl}(f + \Delta f)$. The true power arriving at the cavity under critical coupling with three-stub-tuner is therefore given by

$$P_{cav}(f) = P_{refl}(f + \Delta f),$$

provided that forward power levels are - for simplicity - chosen equal, i.e. $P_{forw}(f+\Delta f) = P_{forw}(f)$. This effect occurs only at or close to critical coupling. Here, the absolute power needed to operate is typically low (<100 Watt). Therefore, a heating of the components of the matching netwrok could not be observed.

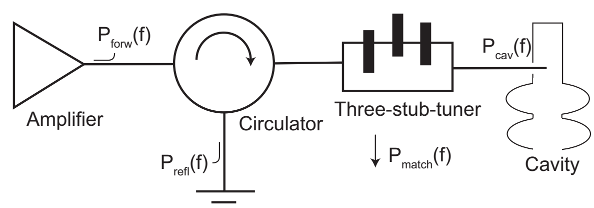

Figure 2: Measuring Q_0 with a three-stub-tuner.

OPTIMIZATION OF Q_0 VIA MAGNETIC SHIELDING

For reaching the highest possible Q_0 values in niobium cavities, good magnetic shielding is paramount. For reasons not fully understood, an ambient magnetic field is trapped in the cavity walls and remains there, driven by lossless circular currents in the cavity walls. For niobium this is valid at fields up to 300 µT [11] which is well above the earth magnetic field of 55 µT. The oscillations of these fluxoids in an external RF-field cause significant losses. As a result, the material exhibits a magnetic surface-resistance R_{mag} that is proportional to the external magnetic field in the instant of the superconducting transition. An empirical relation states R_{mag}/H_{ext}=3.3 nΩ/μT. The BCS resistance [12] is given by $R_{BCS}= A \cdot f^2 \cdot exp(-\Delta/kT)/T$, where f is the RF-frequency, Δ is the energy gap, T is the operating temperature, and A depends on superconducting parameters and (weakly) on f and T. Both add up with other residual losses due to imperfections of the cavity R_{res} yielding an increased total RF surface resistance R_s=R_{mag}+R_{BCS}+R_{res}. This is equivalent to a reduced Q_0, according to $Q_0 = G/R_s$, where G is the shape factor (that is 271 Ω for the TESLA geometry).

For example, a frozen external field of 55 µT increases R_s by 180 nΩ. Thus a cavity with a fairly high Q_0 value of 10^{10} would be downgraded to Q_0=1.3×10^9 when operated without any magnetic shielding.

In order to provide good magnetic shielding, HoBiCaT is equipped with two layers of cryoperm sheets: One is attached to the inner wall of the cryostat at 300 K, a second one is wrapped around the cavity's Helium tank and at 4 K during cryogenic operation. Both shields are optimized for their respective operation temperatures. The residual magnetic field at room-temperature has been measured with a 3-axis flux-gate magnetometer at various positions of the cryostat.

The maximum fields detected inside the double shielding were 0.3 µT, their direction was coaxial with the cavity which is due to the holes for the beampipe in the shield's planar faces. The measured values can be regarded as worst case limits, since the proper ambient temperatures during operation, for which the shields were optimized — will if nothing else improve the performance of the inner cryoperm shield. The influence of frozen flux on the Q_0 can be

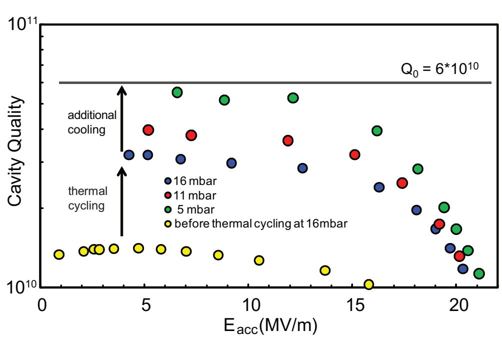

Figure 3: Increasing Q_0 by thermal cycling.

seen in Fig. 3: The lowest curve represents a Q_0 vs E_{acc} measurement immediately after cool-down of the cavity. At the instant of the superconducting transition, the temperature of the cryoperm was much larger than its working temperature, see Fig. 4. Briefly warming the cavity above T_C after all measured temperatures in the cryostat have reached their equilibrium values leads to a significant increase of the quality factor represented by the blue curve with a low-field Q_0 value of 3×10^{10}.

Subsequent cooling to lower temperatures further increases the Q_0 value up to 6×10^{10} which means that the

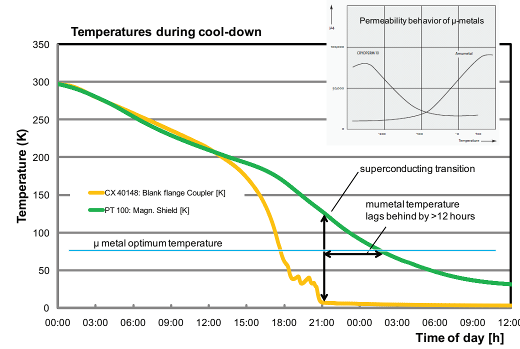

Figure 4: Thermal cycling procedure.

cavity is operating in or near the BCS-limit. Since measurements were performed in one run residual losses must have been the same. This leaves only a decrease in frozen magnetic flux as the cause for the Q_0-increase.

In another test-run with a different cavity, where the temperatures of the cryoperm sheets were recorded with attached thermo-sensors, thermal cycling yielded an increase of Q_0 from 1.6×10^{10} after the first cool-down to 2.1×10^{10}. The respective temperatures of the cryoperm sheets were 200 K at the first SC transition and 45 K at the second transition after the thermal cycling procedure.

REFERENCES

[1] G. Aune, *et al.*, Physical Review Special Topics — Accelerators and Beams, 3 092001(2000).

[2] J. Sekutowicz, Meas. Sci. Technol. 18(2007) 2285-2292.

[3] J. Knobloch, *et al.*, TUPPO017, Proc. SRF 2009, Berlin, Germany.

[4] I. Bazarov, *et al.*, CHESS Report No. 01-003, Cornell University (2001).

[5] K. Umemori, *et al.*, FROAAU04, Proc. SRF 2009, Berlin, Germany.

[6] D. Krämer, E. Jaeschke, and W. Eberhardt (editors), Technical Design Report, ISBN 3-9809534-0-8, BESSY, Berlin, 2004.

[7] M. Liepe, Cornell, *private communication.*

[8] J. Knobloch, W. Anders, and Y. Xiang, Proc. EPAC 2004, Lucerne, Switzerland.

[9] R. Brinkmann, *et al.*: TESLA Technical Design Report, Part II–The Accelerator, DESY Report 2001-011.

[10] W.D. Möller, Proc. SRF 1999, Santa Fe, NM, USA.

[11] C. Vallet, *et al.*, Proc. EPAC 1992, pp1295, Berlin, Germany.

[12] D.C. Mattis, and J. Bardeen, Physical Review vol.111 no.2 (1958) pp.412