HIGH GRADIENT CW MODULES FOR FEL/STANDARD MODULES

Summary of the working group discussions at the SRF2003 workshop

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Abstract

Several proposals for Free Electron Laser Linacs and Energy Recovery Linacs require the continuous-wave (cw) operation of superconducting multi-cell cavities assembled in cryomodules. Some design criteria of cw-cryomodules in respect to cryogenics, higher-order modes damping, fundamental-mode couplers, tuners, microphonics and alignment are discussed.

INTRODUCTION

There are several proposals to build superconducting accelerators as electron beam sources for Free Electron Lasers (FEL). In particular, Energy Recovery Linacs (ERLs) operating in continuous-wave (cw) RF-mode are under development. The need for the design of cryomodules suited for the cw-operation of superconducting multi-cell cavities has motivated the discussions in this working group at the SRF2003 workshop in Travemünde, Germany.

The advantages of the superconducting technology could be successfully demonstrated at the TESLA Test Facility (TTF) VUV-linac [1]. The future European XFEL-linac will be based on this technology [2]. The TESLA cryomodule design has been optimized to operate high gradient 1.3 GHz 9-cell niobium cavities in a pulsed RF-mode at a duty cycle of up to 1%. In view of the realization of the TESLA linear collider project, this cryomodule design achieved low costs per unit length for very long accelerator structures, in order to be competitive in comparison to conventional normal conducting linear collider approaches. The key issues of the TESLA cryomodule design are very low static cryogenic losses and easy assembly procedures, suitable for the industrial production of large quantities. These design goals were reached by the use of long cryomodule cryostats of 12 to 17 m length containing 8 to 12 cavities and long cryogenic structures of up to 2.5 km length for TESLA, only separated by cryogenic strings consisting of 10 cryomodules [3].

Several FEL and ERL proposals require the cw-operation of superconducting cavities, in contrast to the mentioned TESLA, TTF-VUV-FEL and XFEL projects [4]. The cw-operation results in cryogenic losses which scale with the duty factor at given accelerating fields and cavity properties, resulting in dynamic cryogenic losses orders of magnitude larger than in pulsed operation. In addition, high beam loading, the damping of higher order modes, fast RF-tuners at cryogenic temperatures, microphonics and the alignment of cavities and beam focussing magnets have to be reviewed in order to define specifications for a cw-cryomodule. Obviously, a ‘standard design’ for a cw-cryomodule – if such a design could exist at all- is restricted to limited range of RF frequencies (here 1.3 to 1.5 GHz) and similar beam properties. Machines, which are operated at very large beam loading conditions (> 100 mA) and at different frequencies (700 MHz) require different designs, including the optimisation of the cavities.

All these aspects were lively discussed in the working group. This paper tries to summarize the discussion. It does not reflect the opinion of the author in all details.

CRYOGENICS

Superconducting high gradient niobium cavities at frequencies in the range of 1.3 to 1.5 GHz are cooled by means of liquid helium at temperatures below the lambda transition of helium ($T< 2.17$ K), in order to decrease the BCS resistance and increase the unloaded RF-Q_0 and to benefit from the HeliumII heat conductivity properties.

The choice of the operation temperature and the design of the cryomodule has to be matched to the HeliumII heat conductivity properties.

The cavity design and preparation should aim at the highest possible Q_0 values. The accelerating field of the cavities has to be limited in order to achieve reasonable heat loads at temperatures below 2.17 K.

Heat Conductivity of HeliumII

Below the lambda transition of helium the cooling depends on the HeliumII heat conductivity, which is very large compared to other materials - but still limited. The limits result from the HeliumII properties, the liquid helium bath temperature and the dimensions of the helium vessel and the attached tubing. If a maximum heat flow per unit area is exceeded at any position in the bath, the HeliumII will break up and bubble formation will occur. The theoretical maximum specific heat conductivity of HeliumII in a bath for different bath temperatures is shown in Fig.1. For reasonable liquid bath heights (l = 10 – 30 cm) a maximum of 1.48 W/cm^2 results at a bath temperature of 1.9 K. Experimental results show a maximum at a temperature of 1.95 K.

These results are only valid for cryostat geometries similar to the TESLA cavity helium vessel (see Fig.3), where a closed helium vessel is connected by a vertical tube (‘chimney’, ID 54.6 mm) to a horizontal helium two-phase supply tube (ID 72 mm) and the supply tube is filled with liquid to a height of ID/2 of the vertical tube.
(In an open bath, the maximum heat conductivity can be increased by a factor of 3-4.)

As a result for the cryomodule design, a safe heat transfer margin of 1 W/cm^2 should not be exceeded. In respect to the maximum heat transfer in a bath of

HeliumII the cooling can not improved, if the bath temperature is lowered below 1.9 K.

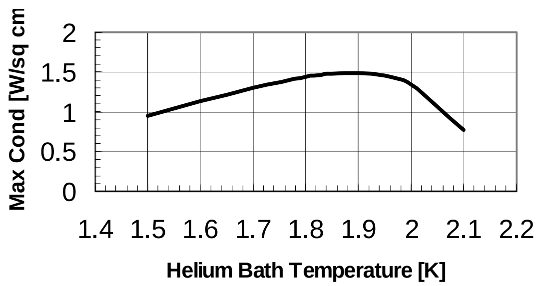

Figure 1: The maximum heat conductivity per unit area of HeliumII as a function of bath temperature. Theoretical values derived from HEPROP [5].

Reasonable Eacc for CW-Operation

9-cell TESLA cavities showed accelerating field gradients up to Eacc = 35 MV/m at $Q >= 5*10^9$ in pulsed operation. At a 5 Hz repetition rate of 0.8 ms pulses this corresponds to a dynamic heat load of 1.8 W/m. Even if $Q_0 = 10^{10}$ is assumed, a cw-operation at 35 MV/m would result in a heat load of 225 W/m. In Fig.2 the dynamic heat load in cw-operation of a TESLA cavity is plotted in dependence of the accelerating field.

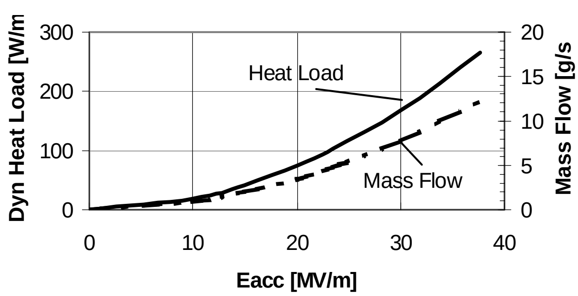

Figure 2: Dynamical heat load and the corresponding helium mass flow for the cw-operation of a 9-cell 1.3 GHz TESLA cavity at Q=1010 versus the accelerating electrical field.

For large structures like linear accelerators the accelerating fields should be limited to 15 – 20 MV/m in order to keep the dynamic heat loads below about 100 W/m.

TESLA CW Cryomodule Layout

At Cornell University and BESSY there are attempts to adopt the TESLA cryomodule design to cw operation [6].

Based on the TESLA/TTF 8-cavity cryomodule, modifications are introduced to allow dynamic heat loads of 45 W per cavity and about 400 W per module (including HOM losses). The modifications are shown in Tab.1 and Fig. 3. In particular, the connection pipe ('chimney') which connects the cavity helium vessel to the two-phase tube and the two-phase tube itself have to be increased in diameter. The diameter of the two-phase tube results from a careful analysis of the helium two-phase flow, which has been carried out in order to establish stratified flow conditions.

In contrast to the layout of the TESLA cryogenic system, where only cryogenic strings consisting of 10 cryomodules are supplied by one Joule-Thomson valve, here each cryomodule is supplied by one Joule-Thomson valve.

Table 1: Design changes for BESSY cw module

	TESLA-TTF	BESSY
‚Chimney' (1)	ID 54.6 mm	ID 90 mm
Two-phase tube(2)	ID 72 mm	ID 96 mm
Gas return pipe (3)	ID 288 mm	ID 288 mm
Connection pipe (4)	ID 72 mm	ID 96 mm

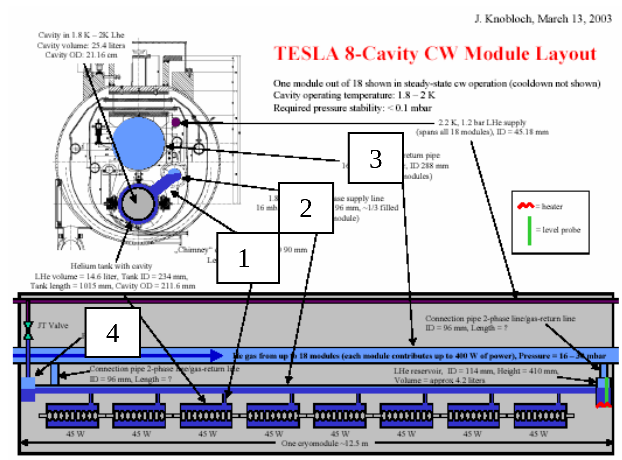

Figure 3: Cross section of the TESLA/BESSY cw module (J.Knobloch,BESSY). The numbers correspond to table 1.

Layout of the Cryogenic Plant

The large ratio of dynamic and static heat loads has to be considered for the design of the cryogenic plant. The 2-K refrigerators have to adopt the varying loads. Bypass regulation schemes should be designed for cold-compressors.

DAMPING OF HIGHER ORDER MODES

ERLs are prone to the excitation of higher order modes (HOM) of the fundamental RF mode. HOMs can dissipate large amounts of energy in the cryostat (in the order of 100 W / cavity).

In principle, HOMs can be suppressed by means of long units of acceleration structures (as proposed for TESLA). Also cavity superstructures, consisting of pairs of two cavities equipped with one fundamental mode RF coupler can avoid the excitation of HOMs to some extent [7].

HOM heat loads should not contribute to the expensive heat load budget of the 2–K cooling circuit, but should be extracted on a higher temperature level. Ferrite HOM-absorbers are widely used [8]. These ferrites are mounted in between the beam tube of adjacent cryomodules and connected to the shield cooling circuits at temperature levels from about 40 K to 80 K. The very large heat loads caused by HOMs in ERLs may even require active cooling of the absorbers. Ferrite HOM-absorbers are suitable also for clean-room preparations.

FUNDAMENTAL RF COUPLERS

The designs of cryomodules and couplers of the fundamental RF modes are linked to each other. Complicated assemblies of couplers at the cryomodules outside the clean-room may jeopardize the performance of high gradient cavities. Therefore couplers should be mounted in the cleanroom as far as possible and the complete coupler-set should be transferred to the cryomodule.

Cold windows should be avoided and warm ceramic windows preferred.

The cryomodule design should allow the in-situ baking of the couplers.

TUNERS

In addition to mechanical tuners, also fast piezo-tuners are needed for FEL linacs and ERLs to keep the energy bandwidths of the accelerated electron bunches small. Piezo-tuners are under development.

The cryomodule design should leave enough space in between the cavities for the tuners. There is the demand for easy access to the tuners in the cryomodules from the outside.

MICROPHONICS

Mechanical resonances occurring in cryomodule cryostats have to be carefully analysed. Long-term observations are needed. Mechanical resonances and microphonic effects should be kept as small as possible, in order to limit the RF-loads. Frequencies ranging from 12 Hz up to 50 Hz have to be considered. The stiffness of the cavities has to be increased. The support of niobium structures by copper-plating seems to be a promising method to enhance the stiffness of cavities.

ALIGNMENT

The alignment tolerances, which could be achieved with the TESLA cryomodule design seem to be sufficient: the axes of the cavities are aligned to the ideal beam axis to within +/- 0.5 mm, and quadrupole axes to within +/- 0.2 mm. The quadrupoles have an additional ‘roll’ tolerance of +/- 0.1 mrad [3].

GENERAL COMMENTS

In contrast to the adoption of the TESLA cryomodule design to cw-operation, there are dedicated cw cryomodule designs available. At JEFFERSON National Laboratory cryomodules for the operation of 8 x 7-cell 1.5 GHz cavities at a cw-load of 250 W at 2 K and an accelerating field of 110 MV were developed [9].

FEL-linacs, which are operated at beam loading conditions > 100 mA and at different frequencies (700 MHz) need complete different designs. These designs have to include the optimisation of the cavities.

CONCLUSIONS

According to the present technologies cryomodules can be properly designed for cw-operation in the 1.3 – 1.5 GHz range corresponding to heat loads in the order of about 50 W per cavity. Any cryomodule design has to be optimised in view of the overall system. It depends also on the overall system if it is favourable to adopt the TESLA cryomodule design to cw-operation or to use dedicated cw-operation-designs.

The cryomodule design is strongly linked to the design of fundamental RF-couplers, tuners and HOM-absorbers.

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