PRELIMINARY THERMAL LOAD CALCULATIONS OF SUPERCONDUCTING DEFLECTING CAVITIES FOR ELETTRA 2.0

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Abstract

Picosecond-long X-ray pulses of moderate intensity and high repetition rate are highly sought after by the light source community, especially for time-resolved fine spectroscopic analysis of matter in the linear response regime. We investigate the upgrade of the Elettra 2.0 diffraction-limited storage ring light source to superconducting radiofrequency transverse deflecting cavities generating a steady-state vertical deflection of selected electron bunches. In this paper, a preliminary design of the cryomodule of the deflecting cavities is reported; both static and dynamic thermal loads are calculated using an analytical approach. The dynamic loads are calculated assuming both bulk Nb and Nb3Sn thin film cavities. The two different solutions involve different cryogenic plants, which will be discussed

SYSTEM OPERATING PRINIPLE

Two superconducting (SC) RF cavities, operating at 6-fold (3 GHz) and 6.5-fold (3.25 GHz) harmonics of the main RF system of the Elettra 2.0 storage ring, establish a steady-state configuration of vertically tilted bunches, with a tilt varying along the ring circumference [1]. Under these conditions, the charge distribution reaches equilibrium in the six-dimensional phase space [2].

The photon beam emitted by tilted bunches exhibits a longitudinal–vertical (t, y) correlation. A vertical slit placed at a given distance from the insertion device (ID) samples the central portion of the elongated photon pulse, thus selecting a shorter time slice at the expense of reduced photon flux. The RF design of the crab cavities is based on the Quasi-waveguide Multicell Resonator (QMiR) concept [3], which exploits a trapped dipole mode to provide transverse deflection of the electron bunch.

CRAB CAVITY RF DESIGN AND LAYOUT

A prototype QMiR cavity was fabricated and successfully tested in a vertical cryostat at 2 K, demonstrating a record transverse kick of 2.6 MV [4]. The crabbing scheme for Elettra 2.0 is illustrated in Fig. 1, while the geometry and main dimensions of a single crab cavity are reported in Fig. 2 [5].

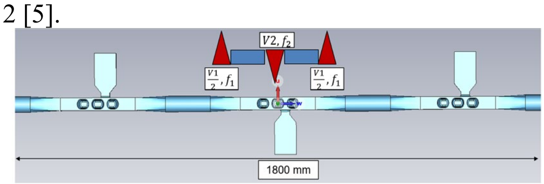

Figure 1: Crabbing scheme for Elettra 2.0.

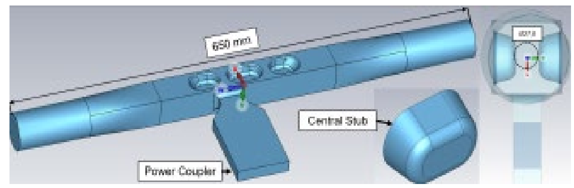

Figure 2: The stub shape for the crab cavities.

RF LOSSES AND THERMAL LOAD IN A PURE NIOBIUM CAVITIES AT 4 K

The effective deflecting voltage determines the dynamic thermal load of the superconducting device. For temperatures below half of the critical temperature (T < Tc/2), where Tc is the critical temperature, the BCS contribution dominates the surface resistance. The geometry factor G=Q0Rsf is a characteristic parameter of the cavity, depending only on its geometry and on the operating temperature.

$$G = Q_0 R_{sf} = Q_0 \omega^2 \lambda_L^3 \mu_0^2 \sigma(T) \exp\left(-\frac{\Delta}{K_B T}\right)$$

where λ_L is the characteristic penetration depth of a static or microwave magnetic field in a superconductor such as niobium, and Δ is the superconducting gap, or binding energy of Cooper pairs.

For the equilibrium temperature $T < T_c/2$, R_{sf} of pure niobium can be expressed in practical units:

$$R_{sf}[\Omega] \approx \alpha \times 10^{-4} \frac{(f[GHz])^2}{T} \exp\left(-\frac{17.67}{T}\right)$$

where usually $\alpha \approx 1.25$ for $T \approx 2-5$ K.

The power dissipated on the internal surface of a tuned superconducting (SC) RF deflecting cavity made of pure niobium, i.e. the dynamic thermal load, can be estimated from the RF surface current losses per period:

$$P_{th} = \frac{\omega_0 U_0 R_{sf}}{G} d_f \equiv \frac{\Delta V_\perp^2}{2R_{sh}} d_f$$

For a pure Nb deflecting cavities system as needed in the Elettra 2.0 light source, as reported in Table 1:

Table 1: Pure Nb features

Feature	**Value**
$Q_0(T)$	2.2×10^{-7}
Surface resistance [μΩ]	5
Thermal load bare cavity s[W]	177

Q_0, R_{SF} AND DYNAMIC THERMAL LOAD FOR Nb_3Sn CAVITY AT 4 K

Nb3Sn, with nearly double the Tc of Nb (indicated with dashed lines), exhibits a significantly lower BCS surface resistance at a given temperature and enables low R_{sf} operation at relatively high temperatures [6].

The dependence of Q_0 on temperature at 1.3 GHz derived from BCS theory for Nb_3Sn, is compared with experimental measurements of a Nb_3Sn cavity as shown in Fig.3

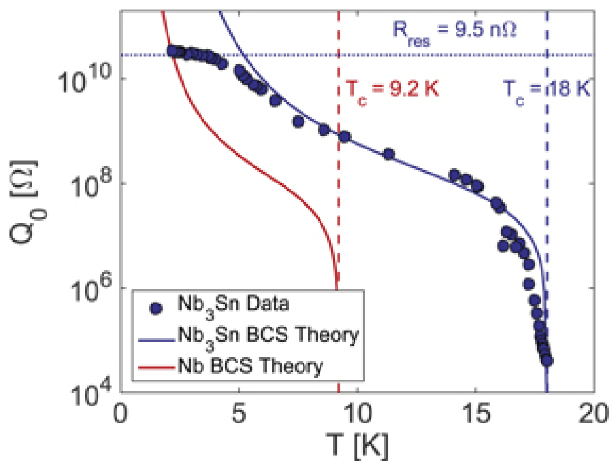

Figure 3: Q_0 vs T for Nb_3Sn and Nb.

Scaling the BCS part $\propto f^2$ from 1.3 $\Rightarrow$ 3.0 and 3,25 GHz and adding the reported ~5 nΩ residual, gives $R_{sf} \approx$ 44 nΩ at 3 GHz and ≈ 50.5 nΩ at 3.25 GHZ.

A deflecting cavity in Nb_3Sn with the same electromagnetic characteristics as that in pure Nb therefore has the following properties reported in Table 2:

Table 2: Nb3Sn features

Feature	**Value**
Q_0(T)	2.2×10^{-9}
Surface resistance [nΩ]	50
Thermal load bare cavity [W]	2

STATIC THERMAL LOAD

The superconducting (SC) cavity is cooled by means of a liquid helium bath at 4.2 K, with the option of sub-cooled operation depending on the dynamic cryogenic losses measured on the prototype. Preliminary esti-mates of the static heat loads at 4.2 K, including con-tributions from the thermal shield stage, are summa-rized in Table 3.

The static heat load is determined by the cryomodule cryogenic design and is independent of the cavity material properties.

The impact of static thermal loads is decisive in an Nb3Sn cavity it is in fact more than 50% of the total cryogenic losses at 4K, while it is negligible for a pure Nb cavity, (1.5%).

Table 3: Nb_3Sn features

Heat Load	**LHe bath[W]**	**Thermal Shield stage[W]**
Radiation	0.7	10
Sensors	0.2	5
Tie roads cacity [W]	0.32	2
Tie rods helium vessel	0.115	2
He inlet pipe	0.03	0.6
He level sensor	0.03	0.6
Safety sensor pipe	0.03	0.6
Burst disc	0.12	2.6
Temperature sensors	N.A.	N.A.
Heaters	0.006	1
Extremity tubes	1	5
Total	**2.551**	**29.4**

COMPARISON OF CRYOGENIC COOLING FOR Nb AND Nb_3Sn CAVITIES

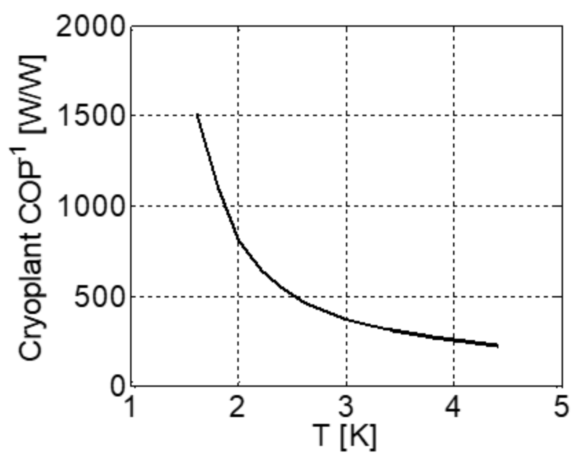

Figure 4: Cryoplant COP-1vs T.

The required electrical power increases significantly with decreasing operating temperature, as shown in Fig. 4. The vertical axis reports the ratio between 1 W dissipated at cryogenic temperature and the corresponding electrical power absorbed from the grid, as a function of temperature.

From a cryogenic perspective, the use of Nb_3Sn cavities enables operation with a cryocooler-based system, even at temperatures below 4 K, thus allowing higher Q_0 values with an electrical consumption of approximately 20 kWh. In contrast, a system based on pure Nb deflecting cavities, with a dynamic load of about 180 W at 4 K, requires a liquefaction plant capable of supplying approximately 250 L/h of liquid helium, along with a gas recovery and storage system, resulting in an overall electrical consumption of about 300 kWh.

CONCLUSION

The analysis shows that the existing Elettra liquefaction plant, which will also supply liquid helium to the Elettra 2.0 facility, does not provide sufficient capacity to support a system based on pure Nb deflecting cavities. In this case, the installation of a dedicated cryogenic plant would be required. Conversely, the Nb_3Sn cavity solution, although still requiring further research and development for cavity fabrication and validation, significantly reduces the impact on the cryogenic infrastructure. In the long term, the Nb_3Sn-based solution appears more sustainable, particularly in view of the reduced power consumption and the increasing uncertainty in the liquid helium supply chain.

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