INVESTIGATIONS OF THE THERMAL BEAM LOAD OF A SUPERCONDUCTING IN-VACUUM UNDULATOR*

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Abstract

Both the resistive wall effect and the synchrotron radiation [1, 2, 3] can warm up the cold bore of a superconductive in-vacuum undulator. For the in ANKA installed superconducting undulator measurements showed that the dominant heat load contribution comes from the synchrotron radiation generated in the upstream bending magnet: 1 W per 100 mA stored current at a beam energy of 2.5 GeV and an undulator gap of 8 mm.

INTRODUCTION

Considering that synchrotron radiation losses increase linearly with beam current, while resistive wall heating losses increase quadratically, it is in principle possible to determine the contribution to the beam heat load from synchrotron radiation and resistive wall losses by measuring the beam heat load dependence on the beam current. The experimental results obtained at ANKA are discussed.

EXPERIMENTAL SETUP

The storage ring compatible cryostat is shown in Fig. 1. The system is cryogen free and is cooled by three Sumitomo cryocoolers (RDK-408D @ 50 Hz) [4]: two of them are cooling the coils to about 4 K and one the UHV tank, which is at 10 K and provides a thermal protection of the coils from the outer world. The cryostat consists of two separated vacuum systems for the cold mass. A UHV vacuum system for the beam and an isolation vacuum system for the coils and the rest of the cold mass. The pressure of the two vacua are monitored. A 300 μm stainless steel foil coated with 30 μm of copper is placed between the cold mass and the beam vacuum. A taper system connects the normal beam pipe with the cold mass and has two functions: 1) smooth transition for wake fields, 2) thermal transition between the cold bore at 4 K and the beam pipe at room temperature. Several temperature sensors are placed on the different elements: coils, UHV tank, taper entrance, taper exit, etc. The undulator can be operated at different gap widths: 16, 12, and 8 mm. The undulator gap can be opened to 29 mm without current in the coils during injection.

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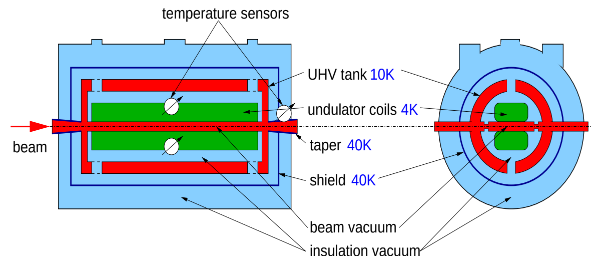

Figure 1: Schematic layout of the vacuum system of the superconducting undulator and the position of the temperature sensors.

RESULTS

In order to protect the undulator from the synchrotron radiation emitted by the upstream magnets a collimator system is located at about 1 m from the entry point of the undulator. The collimator system consists of four independently movable collimators: two horizontal and two vertical. In Fig. 2 is shown the protecting effect of the collimator. When we open the outer one we observe first an incraese in temperature of the taper exit and then an increase in the temperature of the taper entrance. As expected moving in and out the inner one has no effect on the tapers temperatures.

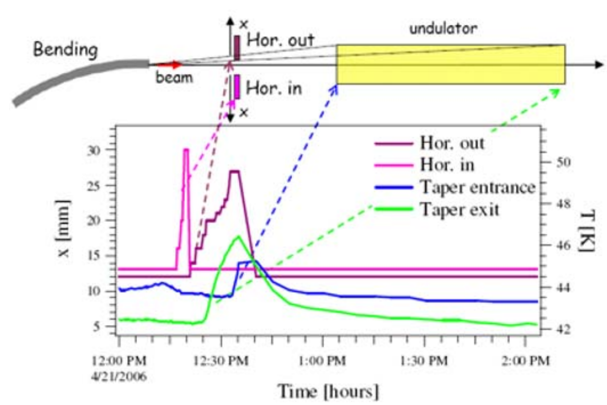

Figure 2: Demonstration of the protecting effect of the coliimator. The positions of the inner and outer horizontal collimator, and the temperatures at the taper entrance and at the taper exit are reported as a function of time.

Fig. 3 shows the temperature at the UHV tank and at the coils during a routine run over two weeks. Both the

UHV tank and the coils are heated by the beam. In order to determine the beam heat load the temperature sensors at the cryocoolers (cooling the coils) were calibrated by a heater in thermal contact with the coils. The beam heat load to the coils is about 1 W. The beam heat load to the coils normalized to 100 mA beam current is 0.7 W. When the heater is switched on (see Fig. 4, gap = 29 mm), only the temperature of the coils increases meaning that the thermal isolation between the UHV tank and coils is very good.

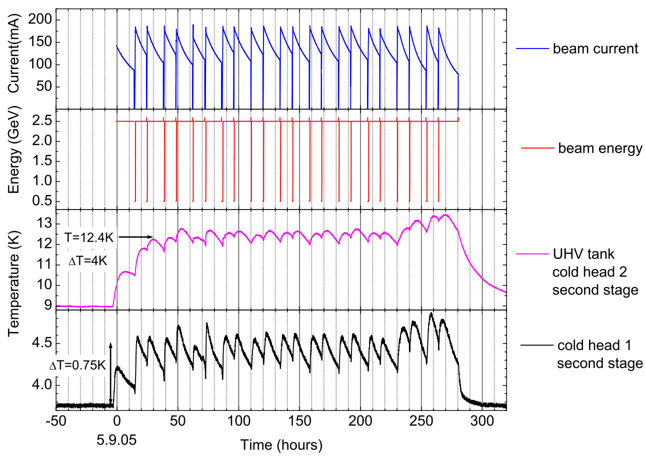

Figure 3: Typical user operation run with open gap (= 29 mm). The beam current, the beam energy and the temperatures of the cryocooler connected to the coils and of the one connected to the UHV tank are reported as a function of time.

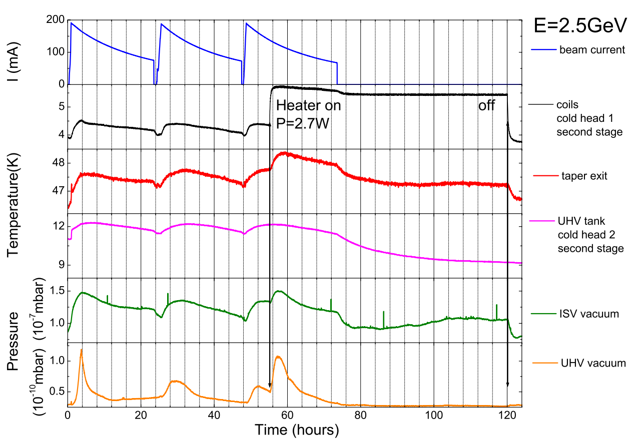

Figure 4: The beam current, the temperature of the coils (cold head, second stage), the temperature at the taper exit, the temperature of the UHV tank and the pressures of the isolation and of the UHV vacua as a function of time. The gap is open (29 mm). When the heater in thermal contact with the coils is turned on all temperatures and pressures increase except the temperature of the UHV tank. This demonstrates that the coils and the UHV tank are thermally decoupled.

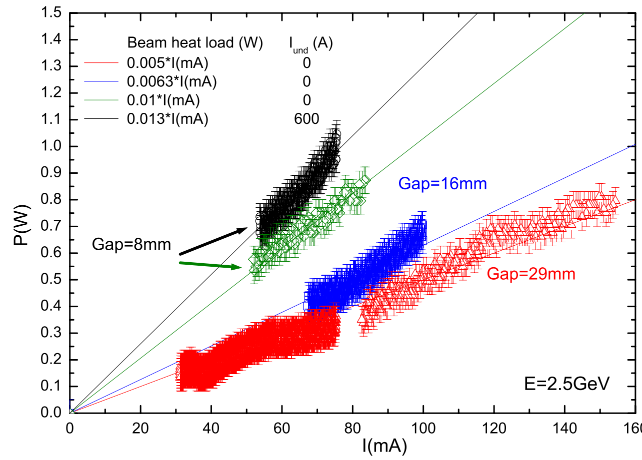

Figure 5: Beam heat load as a function of beam current for different gaps at 2.5 GeV beam energy, when thermal equilibrium is achieved.

Synchrotron radiation losses increase linearly with beam current while resistive wall losses increase quadratically with beam current. In order to distinguish between these effects the beam heat load dependence on the beam current (see Fig. 5) was measured for different gaps at 2.5 GeV beam energy, when thermal equilibrium is achieved. For all cases we observe a linear dependence of the beam heat load on the beam current, which is a strong indication that heating occurs due to synchrotron radiation. The heat load slightly increases by closing the gap. At 8 mm gap the losses for 0 and 600 A are shown: the observed difference is within the error bars [2].

COMPARISON WITH THEORETICAL MODELS

Resistive wall heating The resistive wall heating losses per unit length can be calculated by [3]:

$$P = \frac{I^2}{M f_0 \pi^2 g} \int_0^\infty S^2(\omega) R_{surf}(\omega) d\omega \quad [\text{W/m}] \qquad (1)$$

where I is the average beam current, M is the number of bunches, f_0 the revolution frequency, g is the gap (an equivalent formula is given in Ref. [1]). $S(\omega)$ is the bunch spectrum. Assuming a bunch with Gaussian shape and length σ_z, $S(\omega) = e^{-\frac{\sigma_z^2 \omega^2}{2c^2}}$. $R_{surf}(\omega)$ is the surface resistance. The vacuum chamber is made of a 300 μm layer of stainless steel sputtered with 30 μm of copper. Sputtered copper has usually a Residual Resistivity Ratio (RRR) in the range between 10 and 100 [1]. For copper at low temperature and $RRR > 7$ we are in the regime of the anomalous skin effect [1, 3, 5] and:

$$R_{surf}(\omega) = R_\infty(\omega)(1 + 1.157\alpha^{-0.276}), \quad \text{for } \alpha \geq 3 \quad (2)$$

with $\alpha = \frac{3}{2}(\frac{\ell}{\delta(\omega)})^2 = \frac{3}{4}\mu_r \mu_0 \sigma \omega \ell^2$ where ℓ is the mean free path, $\delta(\omega) = \sqrt{\frac{2}{\mu_r \mu_0 \sigma \omega}}$ the skin depth, μ_r the relative permeability, μ_0 the vacuum permeability and σ the electrical conductivity, and with $R_\infty(\omega) = (\frac{\sqrt{3}}{16\pi}\frac{\ell}{\sigma}(\mu_r\mu_0\omega)^2)^{1/3}$. Assuming $RRR = 100$ and $I = 100$ mA, a bunch length of 10 mm, a gap of 8 mm the resistive wall heating is only 22 mW. This value is much smaller than the value observed of about 1 W and consistent with our observation of a linear dependence of the losses with beam current.

Synchrotron radiation from upstream bending magnet The total radiated power per mrad of arc integrated over

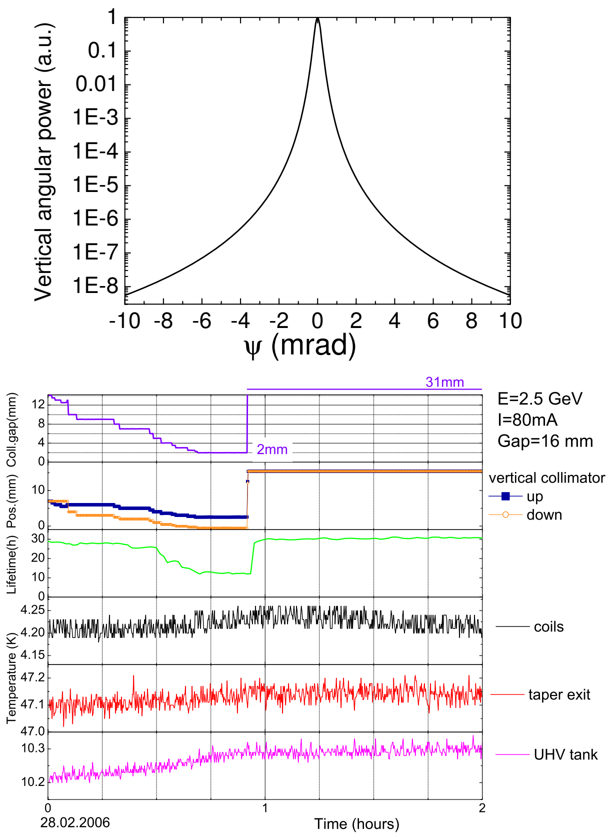

Figure 6: Upper: vertical angular power distribution as a function of the angle ψ between the tangent of motion in the horizontal plane and the point of interest. Lower: for a run with 2.5 GeV electron beam energy, 80 mA beam current and undulator gap of 16 mm, the vertical collimator gap, the position of the vertical collimators up and down, the beam lifetime and the temperatures of the coils, of the taper exit and of the UHV tank are shown as a function of time.

all vertical angles is $P_0 = \frac{eI}{10^3 6\pi\epsilon_0}\frac{E^4}{\rho(m_e c^4)^4}$, where e is the electron charge, I is the beam current, ϵ_0 is the vacuum permittivity, E is the beam energy, ρ is the radius of curvature of the electron trajectory in the bending magnet, m_e is the electron mass and c is the velocity of light. In case of normal operation, with a beam energy of 2.5 GeV and a beam current of 100 mA, the total power radiated per mrad of arc, integrated over all vertical angles is 9.9 W/mrad. Most of the synchrotron radiation will be intercepted by the outer horizontal collimator. The total power passing through the horizontal collimator is 54.45 W. The radiation has a vertical distribution and some of it will heat the horizontal upper and lower surfaces of the vacuum chamber [1]:

$$\frac{\partial P}{\partial \psi} = P_0 \frac{21}{32}\frac{\gamma}{(1+\gamma^2\psi^2)^{5/2}}\left[1 + \frac{5}{7}\frac{\gamma^2\psi^2}{(1+\gamma^2\psi^2)}\right] \quad (3)$$

where ψ is the vertical opening angle between the tangent of motion in the horizontal plane and the plane of interest (see upper plot of Fig. 6). With this in mind it is possible to understand the increase of the observed losses by decreasing the gap (see Fig. 5). The power dissipated in the undulator assuming perfect alignment and a gap of 8 mm is 63 mW. This value is more than one order of magnitude smaller than the observed one. A vertical misalignment of the undulator could be the explanation [6]. To investigate on this we closed the vertical collimator and observed the temperature (see lower plot of Fig. 6), expecting a decrease of the coils temperature. Closing the vertical collimator gap down to 7 mm we observe no change in temperature. By closing the gap further the small increase of 1% in the coils temperature accompanied by a factor of three decrease of the lifetime could be due to electron losses. The failed protection from the vertical collimator is consistent with the idea of a possible vertical misalignment of the undulator [6].

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