MEASUREMENTS OF THE BEAM HEAT LOAD IN THE COLD BORE SUPERCONDUCTIVE UNDULATOR INSTALLED AT ANKA

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Abstract

The beam heat load in the cold bore superconductive undulator installed at ANKA has been monitored for almost two years. The possible sources of the observed heat load as synchrotron radiation from upstream magnets, image currents, photo-excited electrons and ions will be discussed and compared with the experimental results.

INTRODUCTION

Conventional undulators are built with permanent magnets. The advantage of superconducting undulators is that for the same gap and same period length they produce higher fields. However superconducting undulator technology is not yet mature. One of the key issues is the understanding of the beam heat load to the cold vacuum chamber. In this paper we present beam heat load measurements performed at the synchrotron light source ANKA in the superconducting cold bore undulator operating in the ring since March 2005. A more detailed description of the theoretical predictions of the possible beam heat load sources and their comparison with the experimental results is given in Ref. [1].

EXPERIMENTAL SETUP

ANKA is an electron storage ring used as a synchrotron facility. The maximum achievable energy is 2.5 GeV and the maximum current is 200 mA. The revolution time is $T_r = 368$ ns and the machine is normally operated with two trains, each composed of 32 bunches separated by 2 ns. The cold bore superconducting undulator built by ACCEL Instr. GmbH, Bergisch Gladbach, Germany [2], is installed in one of the four straight sections of the ring: the rest of the ring is warm. 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): two of them are cooling the coils to about 4 K and one the UHV tank, which is at 10 K and protects the coils from the external thermal radiation. The cryostat consists of two separated vacuum systems for the cold mass: an UHV (Ultra High Vacuum) vacuum system for the beam and an insulation vacuum system for the coils and the rest of the cold mass. The pressures of the two vacua are monitored by pressure gauges at room temperature. A 300 μm stainless steel foil coated with 30 μm of copper is placed between the cold mass and the beam vacuum. The undulator can be operated at different gap sizes: 16, 12, and 8 mm. The undulator gap can be opened to 29 mm without current in the coils during injection. 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 [3].

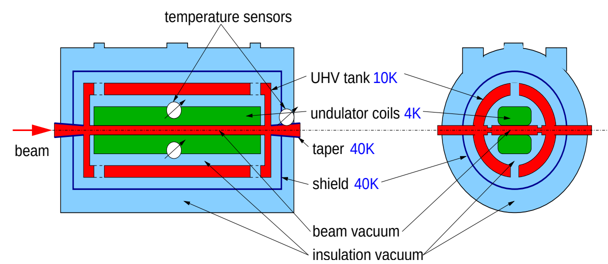

Figure 1: Schematic layout of the vacuum system of the superconducting undulator and the position of the temperature sensors.

POSSIBLE HEAT LOAD SOURCES

Possible heating mechanisms are: 1) synchrotron radiation from upstream magnets, 2) high frequency image currents on the cold surface also called resistive wall heating, 3) ions and electrons accelerated to the walls by the transverse field of the ultrarelativistic beam.

In this paper we present the dependence of the beam heat load on the average beam current I and on the bunch length σ_z. Knowing how the different heat load sources depend on these parameters it should be possible to distinguish between the different heating mechanisms. Synchrotron radiation scales linearly with the average beam current I and is independent of the bunch length σ_z. Resistive wall heating scales as I^2/M where I is the average beam current and M the total number of bunches, and it strongly depends on the bunch length σ_z [4].

Concerning the heating due to electrons and ions a naive model is the following: a charged particle in the vacuum chamber can be accelerated by the transverse electric field carried by the ultrarelativistic bunch and release the energy gained to the wall. The power is roughly the energy gained by the charged particle times the number of charged particles accelerated to the wall per unit time. Since the energy

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is inversely proportional to the mass of the particle the ion contribution can be neglected. A possible source of electrons is the condensed gas layer physisorbed on the surface [1]. The gas layer is formed at low temperatures since energetic particles first hit the surface oxide layer of the vacuum chamber. The desorbed gases then recondense on the surface so that the energetic particles will afterwards hit the gas layer where the molecules are only loosely bound by Van der Waals forces. Since the molecules forming the condensed gas layer have already been desorbed this phenomenon is usually referred to in the literature as "recycling"(see for example Ref. [5]). Our vacuum chamber surface is very similar to the one of the LHC beam screen (300 μm stainless steel with 30 μm of electroplated copper). For such a surface the dominant desorbed gases are H_2, CH_4, CO, CO_2 and H_2O. Of these only H_2 has a non negligible vapour pressure at 4-20 K. In the vacuum chamber of the superconducting undulator the equilibrium pressure is about $2-5\cdot10^{-11}$ mbar, which corresponds to 10^{15} H_2 molecules per cm^2 [1]. Considering the geometry of the vacuum chamber, the number of H_2 molecules on the surface and in the volume have been calculated. On the surface we have $N_{Surf} \approx 10^{17}$ and in the volume, considering $P_{UHV}(300\ \mathrm{K}) = 10^{-11}$ mbar, $N_{Vol} \approx 5\cdot10^{10}$. On the surface there are more than one million times more molecules than in the volume: the surface is a huge electron reservoir.

RESULTS

Beam Heat Load during Normal Beam Operation

During the user operation mode of ANKA a large variation of the heat load and of the UHV pressure is observed. The pressure values reported in this paper are measured at room temperature. The corresponding values at low temperature can be obtained applying the Knudsen relation $P(T) = (T[\mathrm{K}]/300\ \mathrm{K})^{1/2}P(300\ \mathrm{K})$. In Fig. 2 we show the heat load (upper plot) and the UHV pressure (lower plot) as a function of the average beam current I measured over half a year. In all cases the orbit is identical. The different colours refer to different runs over periods of about two weeks. A similar pressure rise with current has been observed in the positron ring at the B factory PEP-II, a warm machine, for high currents and has been attributed to electron multipacting [6]. In the inset of the upper plot of Fig. 2 the beam heat load is shown as a function of the UHV pressure. A correlation between the two measured quantities is observed: above a certain threshold heat load and pressure the heat load increases by increasing the pressure, below it is independent.

Beam Heat Load with Sub-picosecond Pulses

In order to produce short bunches of a few hundred fs ANKA can be operated in the so-called low α mode [7]. The measured beam heat load for a run in the low α mode with one train at E = 1.3 GeV and a gap = 29 mm is shown

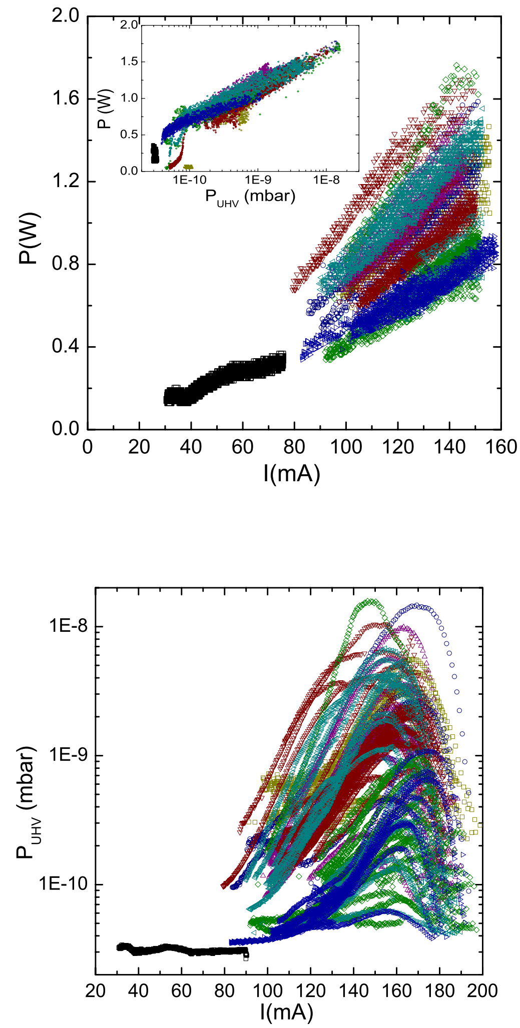

Figure 2: Variation over half a year of the beam heat load (upper plot) and of the UHV pressure (lower plot) as a function of the average beam current. The different colours refer to different runs over a period of about two weeks. In the inset of the upper plot the beam heat load is shown as a function of the UHV pressure. Beam parameters: E = 2.5 GeV, I = 80-200 mA, two trains. Undulator parameters: gap = 29 mm, undulator current = 0 A.

in Fig. 3. The data can be well fitted by the resistive wall heating model using Eq. (2) in Ref. [1] taking into account the anomalous skin effect, assuming a RRR = 100 and a bunch length of 500 fs. The value of 500 fs is consistent with the bunch lengths measured in the low α mode by means of THz edge synchrotron radiation [9]. During normal operation the bunch length varies with beam energy. The heat load induced by resistive wall effects should be higher at lower energies since the bunch length is shorter. This is not the case. So resistive wall heating seems to be dominant for short bunches but not for longer ones. We conclude that another heating mechanism must be responsible for the beam heat load observed during user operation.

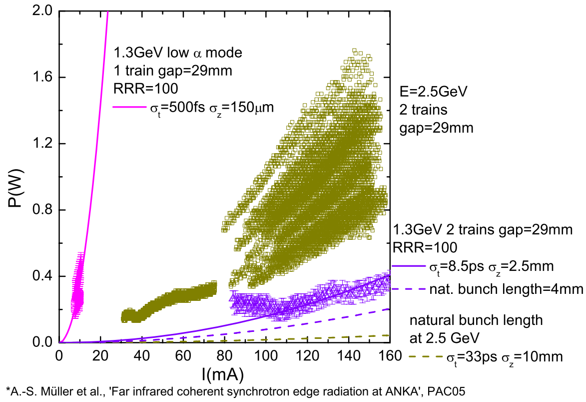

Figure 3: The beam heat load as a function of the average beam current for three different bunch lengths. The four curves are theoretical predictions based on Eq. (2) in Ref. [1] computed for different bunch lengths as indicated. The dashed curves are obtained with the natural bunch length (defined only for the normal optics of the ring i.e., for longer bunches), derived from Ref. [8]. The continuous curves are obtained by using bunch length values adjusted to fit the experimental data.

Pressure Rise and Heat Load due to Electron Bombardment

The sum of the primary and recycling desorption yield of all gas species can be computed using the following equation [1, 10]:

$$\frac{q+q'}{\alpha} = S(n-n_e(s,T)) = SG\Delta P \qquad (1)$$

where $\Delta P = P_{max} - P_e$ with $P_e \lesssim 2\cdot 10^{-11}$ mbar the thermal equilibrium pressure and $G = 1/(k_B\sqrt{TT_{RT}}) = 2\cdot 10^{17}$ cm^{-3}/mbar. For the ANKA cold bore vacuum chamber with gap $=$ 29 mm and average beam current $I = 100$ mA, the photon flux impinging on the lower and upper surfaces is $\dot{\Theta} \approx 10^{16}$ photons/s.

If the heat load observed is generated by electron bombardment and assuming a mean electron energy $\Delta W = 10$ eV, the estimated electron flux for a heat load of $P = 1$ W is $\dot{\Gamma} \approx 6\cdot 10^{17}$ electrons/s. Since $\phi+\phi' \lesssim \eta+\eta'$ [5, 11], we can neglect the photon stimulated desorption (PSD) to the beam desorption flux, so that $q = \eta\dot{\Gamma}$ and $q' = \eta'\dot{\Gamma}$. The observed ΔP ranges from $2\cdot 10^{-11}$ mbar to $8\cdot 10^{-8}$ mbar. For H_2 the mean molecular speed at 4.2 K is $\bar{\nu} = 210$ m/s. The area of the vacuum chamber for a gap = 29 mm is $A = 0.266$ m^2. Applying Eq. (1) we find that the sum of the primary and secondary desorption yields for H_2 $(\eta+\eta')/\alpha$ ranges between 10^{-4} molecules/electron to 4 molecules/electron. Our values are in good agreement with the ones measured at COLDEX [5] that range between 10^{-2} molecules/electron for an electron dose of $2\cdot 10^{19}$ electrons/cm^2 to 30 molecules/electron for an electron dose of 10^{17} electrons/cm^2, considering that in our case the temperature is lower (4.2 K instead of 12 K), the mean electron energy is an order of magnitude smaller (10 eV for a typical $3.6\cdot 10^9$ electrons/bunch instead of 100 eV [5]) and that our electron dose is in some cases much higher (after two weeks of normal user operation it is about $2\cdot 10^{20}$ electrons/cm^2).

CONCLUSIONS AND OPEN QUESTIONS

A non-linear pressure rise with current is observed. This rise might be due to H_2 recycling and/or electron multipacting.

Concerning the beam heat load we have compared the data with theoretical predictions from different models. Synchrotron radiation cannot explain the data since it predicts a linear dependence with current which is not observed. The resistive wall heating model can fit the data for short bunches but it does not for longer bunches.

The electron bombardment model is consistent with the beam heat load and pressure rise observed during normal user operation (longer bunches). Still to be understood is the mechanism responsible for releasing the electrons from the gas layer cryosorbed on the wall of the vacuum chamber.

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