HOM EFFECTS IN VACUUM CHAMBER WITH SHORT BUNCHES*

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Abstract

High luminosity in electron-positron factories requires high currents of very short bunches. SLAC PEP-II and KEKB B-factories are progressively increasing currents gaining more and more luminosity [1-2]. Simultaneously the interaction of high currents and vacuum chamber elements becomes more important for operation of the rings. High Order Modes excited by short intense bunches are propagating along the vacuum chamber, penetrating and dissipating inside vital vacuum elements, like shielded bellows, vacuum valves and vacuum pump. As a result these elements get large temperature rise or temperature oscillations. Often HOM heating has a resonance character. HOM heating of vacuum pumps leads to increasing of the vacuum pressure. High frequency modes "check" the quality of vacuum chamber: they detect small gaps, weak RF screens or feed-through. Smooth tapers and collimators become the source of HOM production. We will discuss the physical nature of these exciting HOM effects.

INTRODUCTION

Super high luminosity factories require high intensity beams of very short bunches. Every bunch bears a very strong electromagnetic field. As bunch travels down the vacuum chamber it may leave a certain part of this field behind due to the field diffraction on irregularities in vacuum chamber. The diffracted fields are often called "wake fields". Fourier transform of the wake fields gives the spectrum of modes. These modes are usually called "higher order modes (HOMs)". After diffraction one part of the wake field follows the bunch, overtakes it and decelerates "head" bunch particles. Other part may propagate in opposite direction. In one turn the bunch will come to the same place and produce wake field again. So a single bunch generates wake fields periodically with a revolution frequency. In the case of a train of bunches the main period is determined by the bunch spacing τ_b , which is in the following relation to RF frequency f_{RF}

$$\tau_b = \frac{m}{f_{RF}} \qquad m = 1, 2, 3, ... \tag{1}$$

Main spectrum lines are:

$$f_n = \frac{n}{\tau_b} \qquad n = 1, 2, 3, ... \tag{2}$$

There can be lines at other frequencies if bunch pattern consists of mini-trains. Example of the beam spectrum of the PEP-II high energy ring (HER) is shown at Fig 1. Bunch pattern consists of 1616 bunches in 24 mini-trains with spacing of 4.2 nsec (m=2) with an end-gap of 150 nsec. Main frequency lines are harmonics of 238.28 MHz. The envelope of the beam spectrum is used for bunch length measurement [3]. Presented spectrum corresponds to the bunch length of 11.4 mm. The bunch current was 1.48 mA in this measurement.

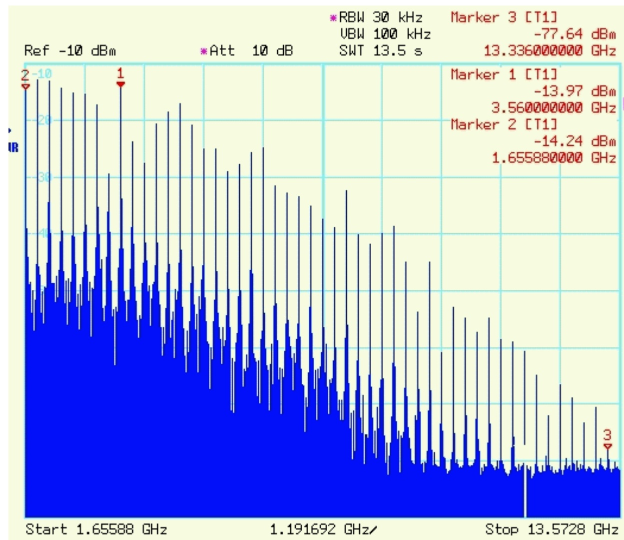

Figure 1: HER beam power on a 10 db/division scale.

A bunch energy loss for the wake field production is described by the loss factor K. Loss factor depends upon the bunch length: loss factor goes up for shorter bunches. If we know loss factor, then we can estimate power loss P of an equally filled beam with a total current I

$$P = \tau_b \times K \times I^2 \tag{3}$$

In a real vacuum chamber wake fields have very complicated structure; however we can classify fields according to distribution of the surface currents, induced by the wake fields. Longitudinal fields will have surface currents with a longitudinal component; and transverse fields will have mainly transverse surface currents. Longitudinal wake fields are mainly generated at symmetrical irregularities of the vacuum chamber, whereas transverse fields are excited at asymmetrical elements. Longitudinal wake field currents propagate easily in the vacuum chamber like image currents of the beam. Transverse wake fields can be captured by shielding fingers of bellows, or vacuum valves, or by screens with longitudinal groves. Penetrating behind the fingers these fields may excite resonance modes at the bunch spacing frequencies (2). Depending on the Q-value of these resonance modes the amplitude of electric field may overcome the breakdown limit and thin fingers may be destroyed. Propagating in the chamber both types of wake fields may be converted one into another. This mode cross-talking mechanism is very important for understanding of the heating issues of different vacuum elements.

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HOMS "CHECKING" SMALL GAPS

Flange connection in a vacuum chamber often contains a vacuum gasket and an inner RF gasket. If a small gap occurs between the RF gasket and flange surface, wake fields can heat the flange. The flange is made of stainless steel, which efficiently absorbs RF power. Some flanges consist of two parts (like a vacuum valve flange) that are mechanically connected but have poor thermal contact. A temperature rise can lengthen the inner part of the flange and make firmer the thermal contact to the outer part of the flange. The heat will then flow to the outer part of the flange, which is air and water-cooled. This cooling lowers the flange temperature and the thermal contact becomes poor again. This "quasi" periodic mechanism may explain the nature of temperature oscillations (Fig. 2) observed at several locations in PEP-II, the SLAC B-factory.

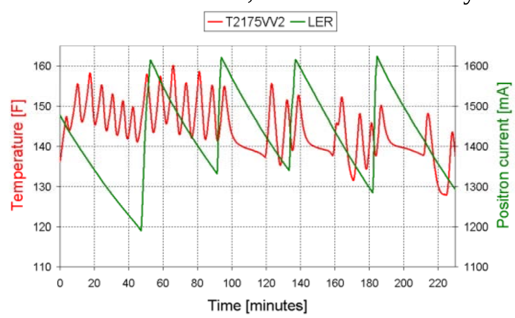
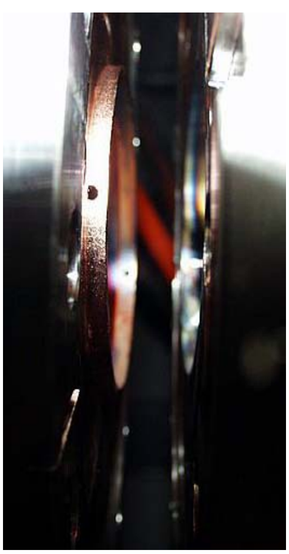


Figure 2: Vacuum valve temperature (°F, red line) and positron current (mA, green line).



Wake fields excited in a small gap by ampere beams have enough amplitude to heat the vacuum valve. The electric component of these fields can be above the arcing limit. Fig. 3 presents the photo of the disconnected flanges and a gap ring. Traces of breakdowns can be easily distinguished by discolorations on the stainless steel flange at the right side. After replacing the ring with one that has the proper size, the RF heating and the temperature oscillations stopped.

Figure 3: Photo of the disconnected stainless steel flanges and RF copper gap ring.

VERTEX BELLOWS

The performance of the whole machine may depend on a single small component. The luminosity of the PEP-II B-factory was limited for a while by excessive heating of a single bellows near the interaction region IP [5-6]. Within the BaBar detector near the IP, where the two beams share a common vacuum chamber, anomalous heating is observed at thermocouples situated on a shielded bellows structure at the juncture of a beryllium beam pipe with a copper vacuum chamber (Fig. 4).

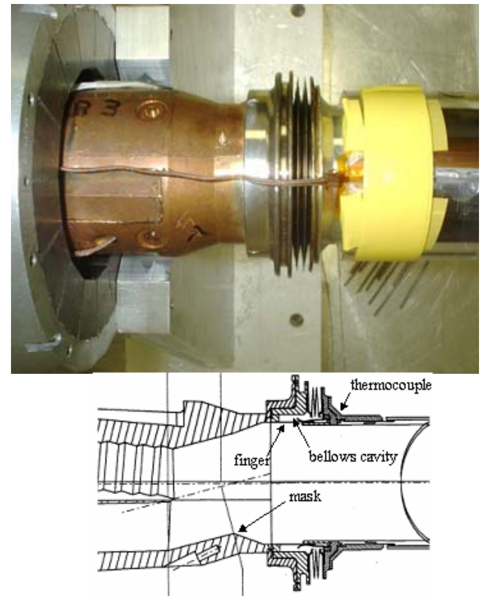


Figure 4: Vertex bellows structure and vacuum chamber showing synchrotron masks and site of thermocouple with high temperature readings.

The heating was determined to be due to excitation of higher order modes inside the bellows cavity. Example of a resonance mode is shown in Fig. 5.

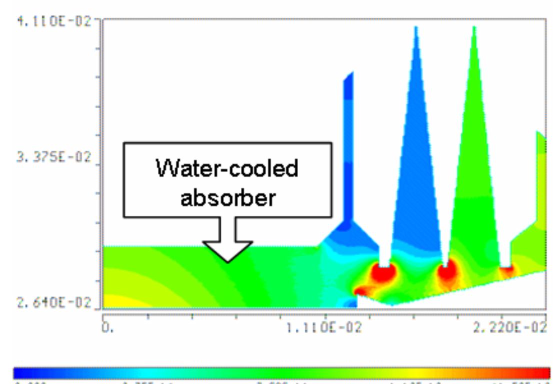


Figure 5: Magnetic energy density of a quadrupole mode of 6.19 GHz.

There are several sources of transverse fields that can easily couple through the RF shield fingers. One of them is the crotch area situated approximately 2 metes far from the vertex bellows; others are tapers and synchrotron masks. Additionally trapped modes that are close to the cut-off modes of the beam pipe may cause the local chamber heating. To solve the heating problem additional water and air cooling was applied. We also developed the project for a new vertex bellows, which will contain a water-cooled absorber inside the bellows cavity [7]. Absorber (Fig. 5) will decrease considerably Q-values of resonance modes and absorb HOM power, and this power will be transmitted outside through the water pipes.

HOMS IN THE ARC VACUUM CHAMBER

A temperature rise has been found in the vacuum chamber elements in one junction of straight and arc chambers. The power in the wake fields was high enough to char beyond use the feed-through for the titanium sublimation pump (TSP). This arc chamber is 5.5 m long and consists of the beam chamber and an ante-chamber. Electromagnetic fields, excited in the beam chamber penetrate into the ante-chamber and then come out through the heater feed-through. A small absorbing ceramic tile was placed near the TSP feed-through outside of the pumping chamber. A thermocouple that was attached to this tile showed a strong temperature rise. In order to study the spectrum of the fields, a short wire antenna was also placed there. The antenna was connected directly to a spectrum analyzer. Measurements showed a wide frequency HOM spectrum with a maximum in the region from 2 to 3 GHz. Based on these measurements a special water-cooled HOM absorber (Fig. 6) was designed and installed in the ante-chamber. As a result, the propagating HOM power in the section decreased and the temperature rise went down. Thermocouple readings from the ceramic tile attached to the feed-though are shown in Fig. 7. The left side of the plot is the temperature before the HOM absorber was installed, and the right side shows the temperature after the HOM absorber installation. The temperature rise decreased by at least a factor of two even though the positron current increased by 40%.

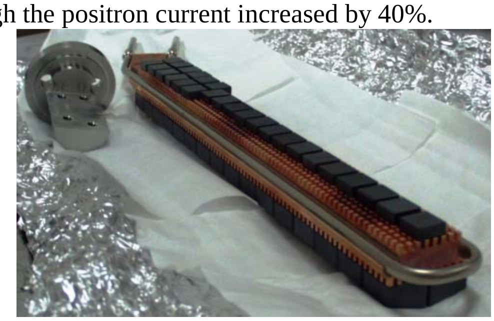


Figure 6: Water-cooled HOM absorber.

Results of measurement of the HOM power dissipated in the absorber during 2003-2004 run are shown in Fig. 8 by the blue lines. The green lines show the positron current. Currently the HOM power reaches 1.2 kW for a positron current of 2400 mA.

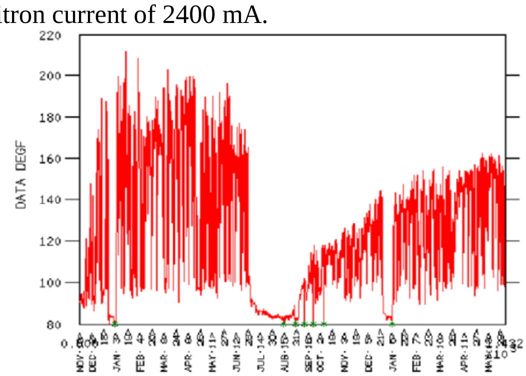


Figure 7: Thermocouple readings (°F) before and after HOM absorber is installed.

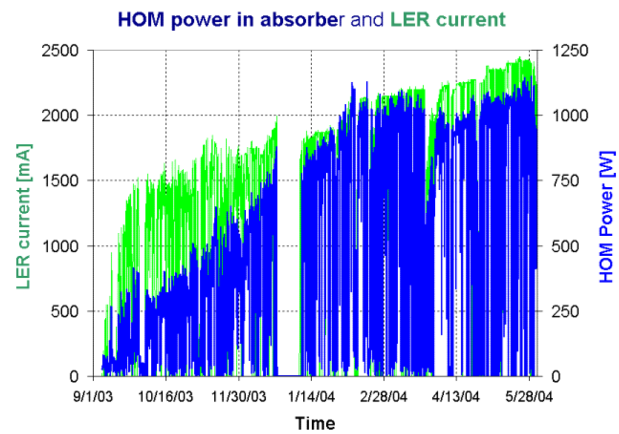


Figure 8: HOM power dissipated in the absorber (blue line) and positron current (green line)

Measurements indicate that the HOM power is almost linear with the RF voltage (Fig.9) and inversely proportional to the number of bunches. These relations give approximation for the HOM power P

$$P = 0.07 \times I^2 \times \frac{V_{RF}}{N_{bunches}} \qquad (3)$$

were I is the positron beam current, $N_{bunches}$ is the number of positron bunches and V_{RF} is the RF voltage.

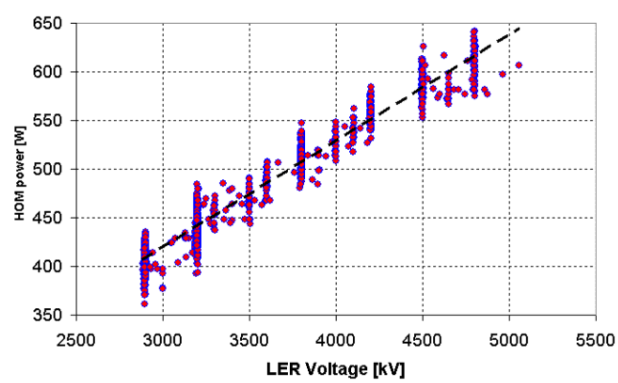


Figure 9: HOM power as a function of RF voltage for a positron current of 1400 mA.

It is worth to note that this absorber also helped to find the source of the HOMs [8].

COLLIMATOR IS THE HOM SOURCE

We did not find any significant correlation of the HOM power with the beam position in the vacuum chamber, but we found a strong correlation with the vertical beam position near upstream vertical collimators which are far away from this chamber. Fig. 10 shows HOM power in absorber (red line), and vertical beam position near 15m collimator (blue line), and 65m collimator (green line). One can see that a 10 mm change of the vertical position near closer collimator reduces the HOM power almost two times. The same (~ 10 mm) change of the beam position in the 65 m collimator changed power in the absorber by additional 10%.

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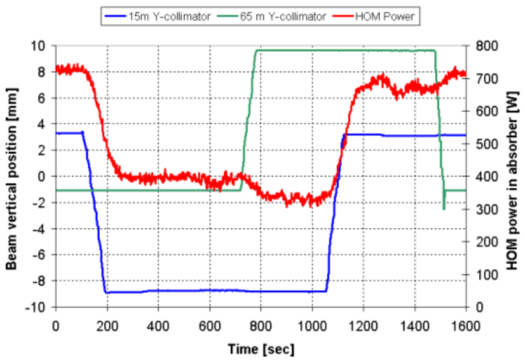

Figure 10: HOM power in absorber (red line) and vertical beam position near 15m collimator (blue line) and 65m collimator (green line).

We observed almost the same power change in the arc bellows, beside this bellows also takes HOM power from the horizontal collimators (Fig. 11).

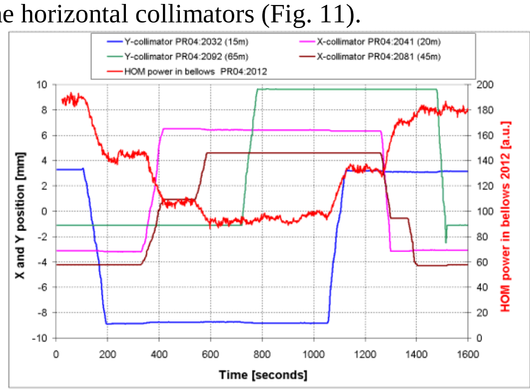

Figure 11: HOM power (red line) in the arc bellows and beam position near vertical (blue and green lines) and horizontal collimators (pink and brown lines).

We performed wake field simulations and results showed very good agreement with these measurements.

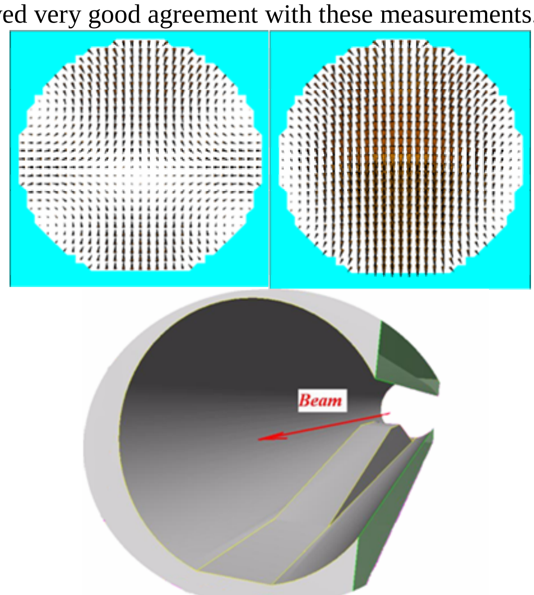

Figure 12: Beams near collimator generate dipole and quadrupole transverse fields.

At the beginning wake fields have quadrupole structure, but then dipole mode becomes the main component of the field. These fields can propagate long distances and penetrate through the shielded fingers into bellows and vacuum valve cavities.

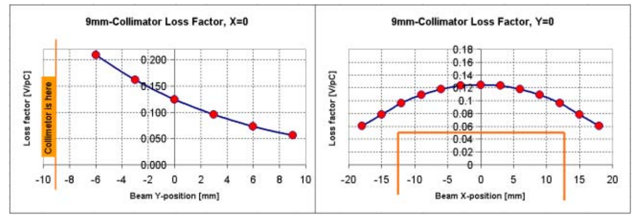

Figure 13: Loss factor as a function of a Y and X beam position.

Calculated loss factor, presented in Fig. 13 confirms that beams excite more fields when they approach vertical collimator in vertical direction, whereas horizontal displacement does not change strongly HOM power. Simulations also confirm the quadratic dependence of the HOM power upon the bunch length (3) in the range of 8 to 13 mm.

We developed a new project for the water-cooled absorber (Fig. 14) to capture the wake fields generated from collimators [9]. Absorbing ceramic tiles coupled strongly to transverse fields through long longitudinal slots, whereas longitudinal field may freely propagate in the chamber.

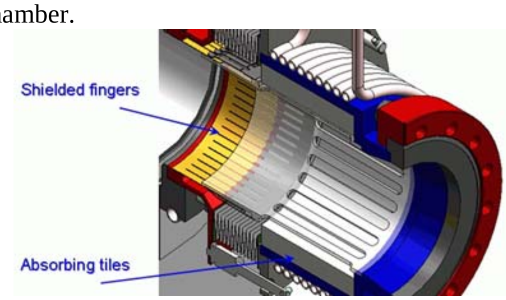

Figure 14: Straight section HOM absorber

BUNCH SPACING RESONANCES

This resonance can occur if the HOM frequency is close to the bunch spacing frequency (2). Many bellows in the PEP-II HER ring demonstrated such behavior. An example is shown in Fig. 15.

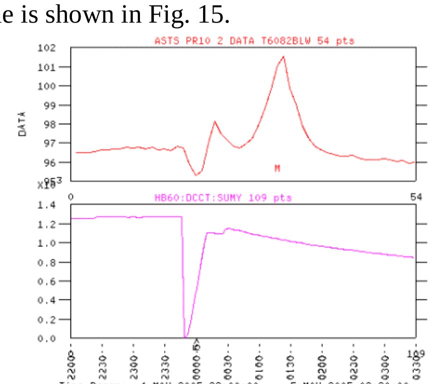

Figure 15: Temperature of the bellows (°F, upper plot) and HER Current (mA, down plot).

The bellows temperature jumps up and then drops down at electron current of 1100 mA during coast running. Fig. 16 shows bellows temperature as a function of electron current during two weeks running.

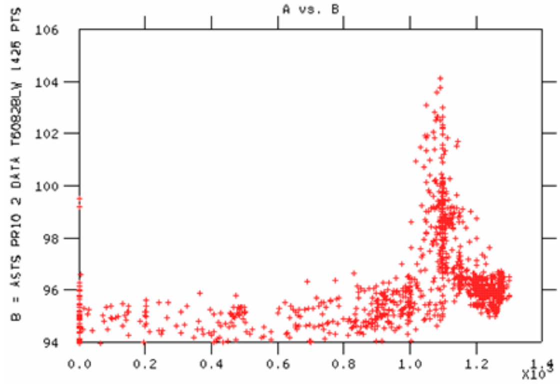

Figure 16: Bellows temperature (°F) as a function of HER current (mA).

This behavior can be explained as variation of the resonance frequency of a bellows cavity within the longitudinal length. A bellows length is changed due to the temperature expansion of the attached vacuum chamber. Resonance with a chamber temperature is shown in Fig. 17. Vacuum chamber of approximately 5 m length gets temperature rise due to synchrotron radiation. So even small change of a chamber temperature can significantly change a bellows length. Q-value of this resonance mode can be estimated by several thousands.

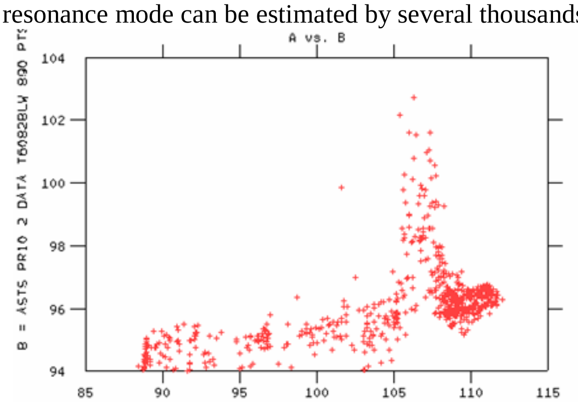

Figure 17: Bellows temperature (°F) as a function of vacuum chamber temperature (°F).

RF SCREENS

Higher beam currents give more HOM effects. Temperature and vacuum rise was observed in several NEG chambers, which are attached to the beam chamber. Generated in the beam pipe wake fields penetrate through the RF screens into pumps and NEG chambers. Antenna placed in the pump high voltage connector showed several high Q-value resonant modes (Fig. 16).

Water cooled HOM absorbers were installed in several NEG chambers [2]. Measured power is shown in Fig. 17 as a function of LER current. More simulations are needed to understand the source and the structure of the wake fields, which can penetrate through the RF screens.

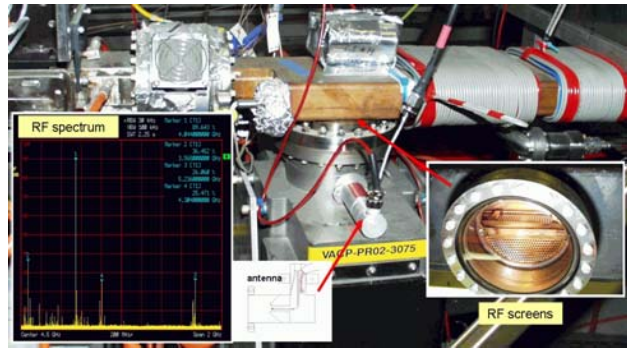

Figure 18: Beam and NEG chamber with a vacuum pump. RF spectrum of a signal from antenna placed inside pump high voltage connector.

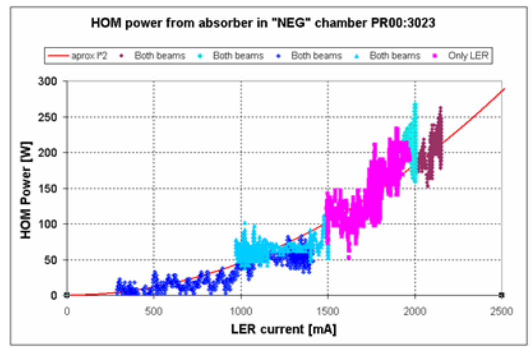

Figure 19: HOM power [W] in the "NEG" chamber as a function of LER current [mA].

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