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Boiling bubbles monitoring for the protection of the LIPAcbeam-dump

David Rapisarda [a,*], Pedro Olmos[a], Beatriz Brañas[a], Fernando Arranz[a], Daniel Iglesias[a], Joaquin Molla[a].

[a] *CIEMAT, Avda. Complutense 22, 28040 Madrid, Spain*

Abstract

Local boiling in the cooling water of the LIPAc beam dump is an indication of abnormal conditions and will be used to trigger a fast beam shutdown through the Machine Protection System before any mechanical damage occurs. A prompt detection of boiling can be done thanks to the use of hydrophones recording the boiling sound. The sensors must have a broad and flat frequency range as well as a high sensitivity. In order to study the characteristics of the sound produced by localized boiling in different situations, an experiment has been carried out on a 1:1 prototype of the beam dump. A hydrophone was placed inside the cooling loop and the sounds produced by the bubbles were recorded. The heating was provided by means of an isolated "hot finger" giving up to 300 W/cm^2 of controlled localized power density. The experimental setup allows the characterization of the time-spectral content for different cooling flows, which is required for the design of the final protection subsystem.

Keywords:

Boiling detection, Acoustic, Beam dump, IFMIF

1. Introduction and design requirements

The LIPAc (Linear IFMIF Prototype Accelerator) is a prototype of one of the two IFMIF accelerators [1]. Its objective is to validate the low energy part (9 MeV) of the IFMIF linacs (40 MeV, 125 mA of D+beam in continuous wave). It will not have a target and hence a dump is needed to stop the deuteron beam. The LIPAc beam dump consists of a copper cone, 2.5 m long, 0.3 m in diameter, 5–6.5 mm thickness, whose inner surface absorbs a power of 1.12 MW (with up to 2.5 MW/m^2 peak power density in nominal conditions). This piece will be cooled by water in counter-beam direction at high velocity through an annular channel formed between it and a second piece (shroud) [2], see Fig. 1. After cooling the cone, the water returns through the space between the shroud and a stainless steel cylinder.The parameters of the cooling loop (108 m^3/h, 31◦C and 3.5 bar absolute pressure at beam dump entrance) have been selected in such a way that no boiling is expected during normal operation. However (see next section), they have been adjusted to obtain temperatures at the water-copper interface close to the saturation point, so that if the beam conditions change outside allowable margins, the beam dump will reach locally temperatures above saturation. In this situation, hydrophones are foreseen for measuring the sound produced by bubbles in the coolant water, giving an alert to the operator or an alarm to trigger the beam shutdown through the machine protection system before any mechanical damage takes place. Macroscopic pool or flow boiling behaves as the classical Nukiyama curve states [3] (Fig. 2). Boiling begins (point A) at a temperature slightly greater than the saturation one, forming isolated bubbles at defects (V-shape [4]) on the surface. When the temperature rises beyond point B, bubbles form at high rates and variety of sizes even developing jets of voids. Beyond the critical point C, a vapor film is developed on the surface thus decreasing the bubbling rate. Zone AB, where the first bubbles appear, is usually referred as"incipient boiling".

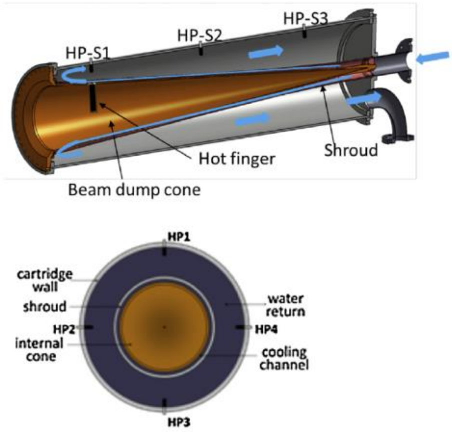

Figure 1 Beam dump cartridge longitudinal and transverse sections showing the positions where the hydrophones will be installed and the hot finger position in the experiments.

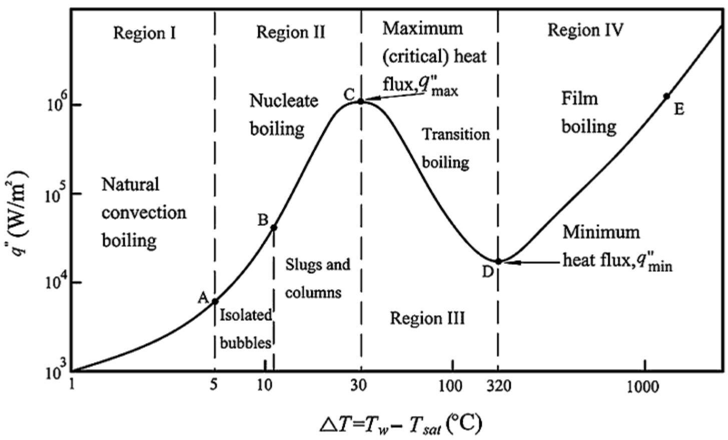

Figure 2 Nukiyama curve.

Boiling bubbles produce sounds as a consequence of sudden overpressure caused by departures from nucleation sites, coalescence and collapsing of free bubbles [5]. These overpressure transients contain frequency components related to the bubble sizes through the Minnaert resonance [6]. Some of these components fall within the human hearing range (1–20 kHz), being macroscopic bubbles (diameters larger than 1 mm). Others, due to micro (or even nano) bubbles produce inaudible sounds whose frequency largely exceeds 100 kHz. There are many works in the literature dealing with the sound produced by boiling bubbles [7–9].Most of them focus on boiling without drag forces or that produced in pipes with relatively low flow rates and heating along a good part of their length. The problem involved in the beam dump is significantly different because of the very high flow involved (which leads to velocities between 4.5 and 8.5 m/s in the cooling channel) and the possible overheating in localized regions of the cone. This justifies the performance of some tests to confirm the feasibility of the acoustic detection of localized incipient boiling under such conditions.

Table 1 Beam dump cone maximum temperature and stress for different input beams.

Error effect and value	Maximum internal temperature (ºC)	Maximum external temperature (ºC)	Maximum stress (MPa)
nominal	137.78	108.69	56.4
closed 10 %	145.88	112.87	68.9
closed 20 %	160.42	122.17	78.8
closed 30 %	187.94	142.07	94.4
opened 10 %	131.79	105.85	64.1
opened 20 %	126.79	103.87	56.0
opened 30 %	123.22	101.21	133.0
steered_x ±4 mrad	145.22	113.83	93.1
steered_x ±6 mrad	154.58	122.41	130
steered_x ±8 mrad	165.67	131.40	166
steered_y ±4 mrad	158.03	124.94	91.7
steered_y ±6 mrad	168.41	133.53	127

2. Beam dump monitoring and protection via hydrophones.

Due to the interaction between the D^+ beam and the copper cone, the beam dump becomes highly activated thus preventing any repair or maintenance operations. Therefore it must be guaranteed that the beam conditions stay in the range for which the beam dump has been designed. For that, beam instrumentation is used (beam position monitors, profile meters, beam loss monitors, etc.). Additionally direct monitoring of the operation at the beam dump itself is done. As they cannot be repaired, sensors used for beam dump monitoring should be highly reliable and rad-resistant. After a first analysis direct monitoring of the inner cone via thermocouples or strain gauges was discarded, as the instruments or cables would be immersed in the coolant flow; thus affecting the overall cooling. Therefore, it was decided to install hydrophones in the return coolant duct between the cylinder and the shroud, to detect undesired coolant boiling and ionization chambers at the outer surface of the cartridge, to provide indication of abnormal power deposition profile. The complete beam dump cartridge is surrounded by a dedicated shielding [10] which permits the installation of electronic equipments close to the sensors.

Sound detection via hydrophones has been shown to be a reliable indicator of beam displacement, improper steering, or over-focusing at the Low Energy Demonstration Accelerator, LEDA[11]. In fission reactors, these sensors have been used to detect possible boiling in the reactor vessel [7] and in other boiling systems they have been used to study the characteristics of sound emission [12]. For the LIPAc beam dump it is foreseen to install a total of twelve sensors (four sensors at each of three axial locations), to provide redundancy and information on bubbles origin (Fig. 1).Three different operating conditions have been defined: normal, upset (off-normal beams) and emergency (excessive errors on beam shapes). The beam dump has been designed for beams within the normal range (up to 10 mm misalignment, nominal divergence ±10 %), which includes all foreseen beams taking into account the possible static and dynamic errors. Table 1 shows the maximum temperatures and stresses at the beam dump cone for different cases. Emergency conditions (red rows) have been defined based on material limits; normal range is marked in green and intermediate conditions (upset) in yellow. Mechanical damage has been assessed following standard low temperature check rules (ITER SDC-IC),considering a minimum value for the yield stress of the beam dump copper (electrodeposited) of 197 MPa at 150◦C. With the exception of too opened beams, saturation conditions are reached at the copper-water interface in emergency situations:

- Too focused beams, with divergence 30 % lower than the nominal value.

- Steered or misaligned beams with an angle deviation from the beam dump axis up to ±8 mrad in x-direction or ±6 mrad in y-direction (or beam misalignment up to 20 mm in x and 15 mm in y-direction).

As stresses under those conditions are still lower than limits, the prompt detection of these situations can be used to correct or shutdown the beam thus protecting the beam dump.

3. Experimental set-up.

To check the feasibility of the prompt boiling detection with hydrophones, and learn about the amplitude and frequency spectrum of the signals, experiments have been performed using a 1:1 prototype [13] of the beam dump installed in a hydraulic circuit. This setup has been used to validate the cooling design, to learn about the best way to operate the cooling circuit, to verify pressure losses and to check the magnitude of flow induced vibrations [14]. A localized energy deposition greater than the one expected in the beam dump and enough to produce temperatures at the water–metal surface above saturation has been experimentally simulated using a home-made hot finger installed in the cone. The hot finger (Fig. 3) consists of a copper rod with a wrapped wire heater that provides a maximum power of 240 W. The heater has been powered with a regulated DC supply (up to 90 V) to avoid spurious vibrations of the wire (and hence sound) that normally appear when the AC mains is used. Incipient boiling is the region of interest to perform a prompt detection of abnormal situations. Thus, the setting point of the power controller was set a few degrees higher than the saturation temperature.

The finger tip has 1 cm diameter, giving a maximum power density of 300 W/cm^2. Thermal isolation from the cone is achieved by means of a Macor ceramic ring (1.46 W/m K). The assembly copper-wire is thermally isolated with a glass fiber webbing (0.05 W/m K). Two K-type thermocouples monitor the temperature in the middle and top (at 1 mm from the interface with the water) regions of the finger. The hot finger position can be seen in Fig. 1. Sound is detected with a high sensitivity, broadband hydrophone, type 8103 from Brüel&Kjær (HP8103), immersed in the water. This hydrophone has a sensitivity of 0.0967 pC/Pa that, once converted to voltage in a conditioning amplifier provides a final response of 26.1 µV/Pa. Signal is recorded by a PC audiocard (SoundMAX) that digitizes the sound at 44,000 samples per second, 24 bit resolution. HP8103 has been located at HP-S1 position, Fig. 1.

Radiation resistance of HP8103 is guaranteed by the manufacturer up to 5 × 10^7 rad. At accelerator full power neutronics calculations have shown that absorbed dose in the HP position is less than 350 Gy/h. According to this value the HP could properly work, at least, 9 complete months (8 h; 5 days per week). In any case, commissioning time is not completely decided at this moment and the sensor will work several months at much lower doses (from 0.1 to 100% duty cycle). During this period, ionization chambers will be tuned for supporting interlock function of hydrophones.

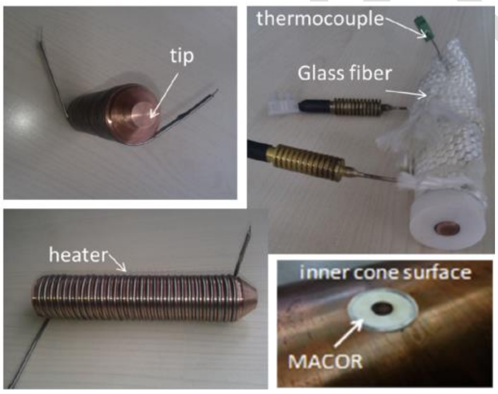

Figure 3 Hot finger. The lower right picture shows it mounted at the cone and viewed from the water side.

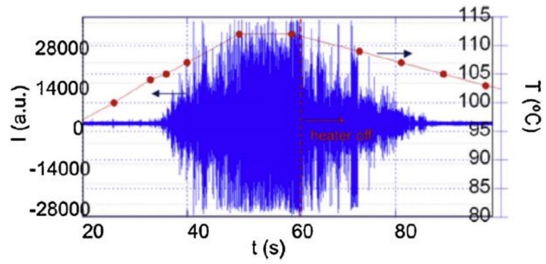

Figure 4 Raw signal from HP8103 for stagnant water conditions and temperatura measured at 1 mm from the hot finger tip.

4. Sound characterization at stationary conditions

Characterization of the sound produced by boiling bubbles in stagnant water has been performed. The usual pool boiling conditions are fulfilled, with the difference that both the convection currents and bubbly flows occur inside a horizontal narrow channel. Pressure was kept at atmospheric level, so that the saturation temperature is close to 100◦C. Fig. 4 shows the HP8103 signal during a heating–boiling–cooling cycle for the entire 20 kHz band. After switching the hot finger power on, the temperature at its tip rises up to 112◦C. Then the power is switched off and the finger is allowed to cool back to saturation. It can be seen that boiling begins at 34 s and ends at 85 s. Temperatures given by the thermocouple at 1 mm from the water surface, measured at these two instants, are around 5◦C higher than the saturation ones. The signal amplitude rise is faster than its decrease because the former occurs while heating is on whereas the cooling is free, only affected by thermal inertia and natural convective cooling.

The spectrogram of this record is given in Fig. 5. Boiling starting and ending times are clearly visible, as well as the concentration of sounds around three separate bands located at 1.5, 2 and 3.2 kHz. Outside the boiling zone, the background is quite low in comparison with the amplitude of the sound due to bubbles. Applying the Minnaert relation, relatively big bubbles (4.2, 3.2 and 1.9 mm, respectively) form in this initial stage of boiling at stationary conditions. This fact is related to the size of nucleation sites and, more importantly, to the fact that the bubbles develop freely.

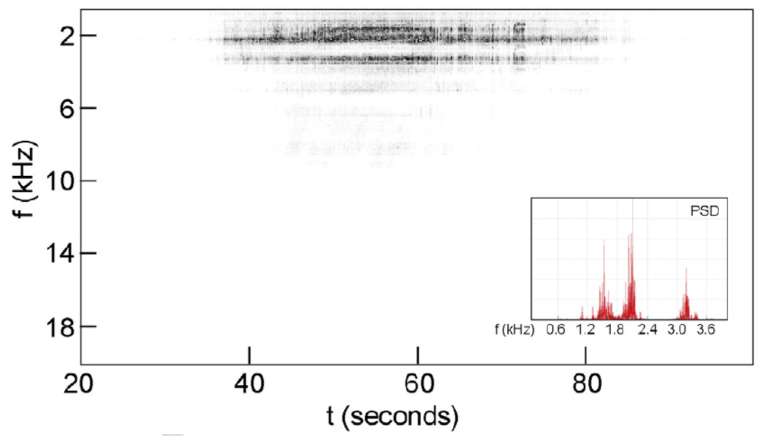

Figure 5 Spectrogram and power spectral density (PSD) of record shown in Fig. 4.

5. Measurements at flowing conditions

5.1. Measurements at low flow regime

When the water flows situation changes radically and the sounds recorded from the boiling process greatly differ from those obtained without flow, even for low flow rates (0.25 times the nominal value). Besides the appearance of the pump noise, which contributes to increase the background (making necessary a high-pass filtering @500 Hz), the shape and bubbles distribution do not resemble the patterns obtained at rest. This fact is seen in the record shown in Fig. 6, which was obtained for a flow of 25 m^3/h and a pressure of 3 bar at the beam dump entrance (expected pressure at the hot finger position of 2.9 bar corresponding to a saturation temperature of 133◦C).

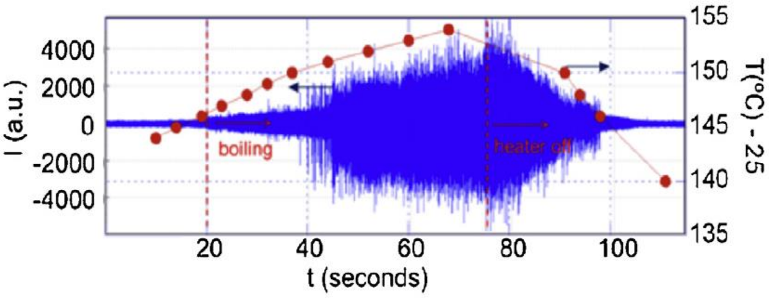

Figure 6 Signal from HP8103 at 25 m³/h high pass filtered (500 Hz) and temperatura measured at 1 mm from the hot finger tip.

Fig. 7 shows the spectral content corresponding to the record from Fig. 6. Due to a richer variety of bubble sizes, the spectrum covers a good part of the audio range. It is arranged in bands that correspond to diameters from few mm to 0.3 mm. The spreading of the two intermediate frequency clusters obtained in the stationary case to this broad spectrum can be explained by the effect of the flow on the bubbles departing from the hot finger. Although it has been said that the flow is "slow", 25 m^3/h in the thin cooling channel corresponds to a non-negligible velocity of 1.4 m/s. In fact, this flow is able to drag violently the bubbles before they reach the size dictated by the hot finger temperature. Moreover these "immature" bubbles, once pulled out from their nucleation sites, are forced to crash one into another thus accelerating their collapses, explaining the great variety of small diameters involved.

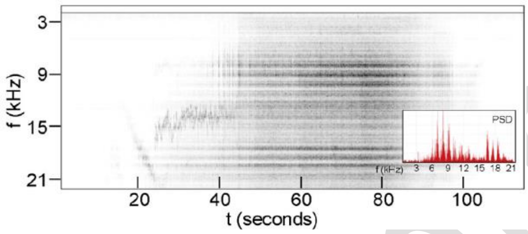

Figure 7 Spectrogram and PSD of record shown in Fig. 6.

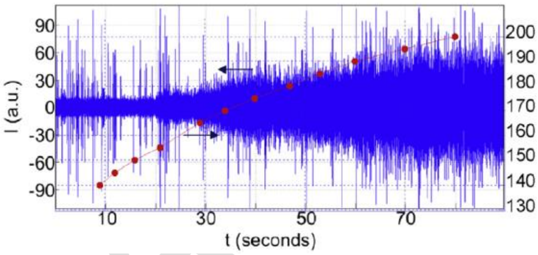

Figure 8 Signal from HP8103 at 108 m³/h (band-pass filter 12–13 kHz) and temperature measured at 1 mm from the hot finger tip. As the circuit during the experiments was not completely degassed, air bubbles are seen as short spikes.

5.2. Boiling at nominal operation conditions

When the flow rises up to its maximum value (108 m^3/h) boiling also happens, though, due to the large heat removal capability of the cooling system, significantly higher power is required. For the used configuration, with the hot finger dimensions and power mentioned before, boiling does not develop until the temperature rises well over the saturation one (in this case, the pressure at the hot finger position is around 3.8 bar, corresponding to a saturation temperature of 141.5 ◦C). This means that we would be moving along the part

BC of the boiling curve, but without the natural violent bubbling phenomena related to increments of temperature in excess of 50 ◦C.

Although not showed, the bands of well separated frequencies that appeared in the low flow case seem to evolve towards a narrow zone where the boiling is evident, even among the large number of isolated bubbles due to degassing events. Fig. 8 plots the heating part of the curve, beginning at 18 s. This means that, instead of the myriads of diameters that would be expected if pool boiling were occurring, the turbulent flow drags the bubbles almost immediately after their nucleation has taken place thus yielding a more uniform distribution of sizes and consequently a much poorer spectrum of sounds.

6. Conclusions

Results showed in Section 5 demonstrated that, in relevant operating conditions for the beam dump, incipient boiling could be effectively detected by the sound produced by bubbles. Table 2 shows a comparison of the signal to noise ratio (SNR) measured at different flow rates. These values have been calculated for all cases in the same conditions, by using a broad band-pass filter(3–15 kHz). Experimental results show that for larger flow rates (and therefore larger water velocities in the cooling channel) the SNR decreases. Thus, bubble detection in this annular channel configuration is more difficult at higher flows, but sufficient to be measured.

The frequency bands of the bubbles have been found to depend on the different flow rates. The band-pass filter used in the protection system should therefore be adjusted depending on the flow to optimize the signal to noise ratio. Final tuning must be done once the beam dump is installed at its final site. At the sight of the results obtained in Section 5.2, where no traces of sound due to the apparition of jets of bubbles were obtained, a deeper study of the boiling phenomenon at high flow could be necessary to achieve a good knowledge of the whole process. This will be the subject of a next paper.

Table 2. SNR recorded by the HP8103 for different flow rates up to the nominal operating

$Q(m^3/h)$	SNR(dB)
0	37.08
25	30.65
54	15.61
108	8.65

Acknowledgments

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