EXPERIENCE WITH THE CONDITIONING OF LINAC4 RF CAVITIES

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Abstract

Linac4, the future H$^-$ injector of the PS complex at CERN has reached the hardware and beam commissioning phase. This paper summarizes the experience gained in RF conditioning of the DTL, CCDTL and PIMS cavities. The behaviour in conditioning of these cavities strongly depends on the cavity type and assembly conditions. Examples of conditioning history and vacuum measurements before, during and after conditioning are discussed.

INTRODUCTION

The main accelerating section of Linac4 consists of 3 Drift Tube Linac (DTL), 7 Cell Coupled Drift Tube Linac (CCDTL) and 12 Pi-Mode Structure (PIMS) cavities. The Linac4 cavities operate at 352.2 MHz and the beam duty cycle is 0.08%.

GENERAL CHARACTERISTICS OF THE LINAC4 RF CAVITIES

Conditioning time and efficiency strongly depends on the cavity type, material and its history of surface treatment. These characteristics are therefore outlined in the following before evaluating the conditioning process.

DTL

The DTL cavities have been designed and assembled at CERN with parts manufactured in Spanish industry. The stainless steel DTL tanks were copper-plated at CERN. Drift tubes are made from machined 3d forged OFE copper pieces that are joined by electron beam welding. The drift tubes contain focusing magnets (PMQs) in vacuum made from stainless steel holders with inserts of permanent magnetic SmCo material. The mechanical complexity of the PMQs with a considerable surface area (7489 cm^2 for 45 mm length PMQ) and positioning screws leads to elevated outgassing ($7.4 \cdot 10^{-6}$mbar · l/s for 45 mm length PMQ). Outgassing takes place through the beam apertures of the drift tubes and passes through high field areas between drift tubes. The presence of outgassing products in that area increase the probability of breakdowns. The permanent magnets of the DTL cavities come in two species of 45 mm and 80 mm length that have been made by two different manufacturers. The cavities have been vacuum sealed with all-metal spring loaded seals in order to keep outgassing rates low and to guarantee a good RF contact. The peak electric field in the first cells of tank 1 have been reduced by design in order to reduce the probability for breakdowns [1].

CCDTL

The CCDTL cavities have been constructed at VNIITF, Snezhinsk, while the drift tubes and supports were made at BINP, Novosibirsk. All structures were then assembled and tuned at BINP before shipment to CERN [2]. The cavities are copper plated and contrary to the DTL cavities the drift tubes are joined by vacuum brazing and then electron beam welded to the stem. As the copper pieces are heated during the process of brazing, they become soft. In general soft copper enhances the probability of breakdowns due to an increased amount of crystal dislocations [3]. Considering the RF design, the CCDTL cavities consist of accelerating cells and coupling cells. The coupling cells couple the RF power from the centre cavity to the side cavities. As the structure operates in the pi/2 mode the coupling cells are nominally field free during the pulse flat top. Between the accelerating cells the phase difference is $\Delta\phi = \pi$. The coupling cells are positioned off-center to allow the positioning of external magnets on the beam trajectory. The excitation of multipacting in the coupling cells prolongs the conditioning of the accelerating cells. As long as multipacting persists, accelerating cells fed through coupling cells do not condition efficiently as they do not receive the full power that corresponds to nominal field levels. The conditioning of the CCDTL cavities thus progresses consecutively from the central accelerating cells to coupling cells and finally to the outer accelerating cells.

PIMS

The PIMS cavities were designed and assembled at CERN with parts manufactured in Poland. They are machined from 3d forged OFE copper rings and disks and joined by electron-beam welding. Only the central copper ring sees a brazing operation for the assembly of ring and RF input port [4]. The material and assembly techniques of the cavities provide a good basis for a rapid and effective conditioning.

During RF operation the forward and reflected power to the cavities is measured through directional couplers on the feeding waveguides and the power inside of the cavities is monitored with field probes. The vacuum pressure is also monitored and used as an interlock signal to stop the RF at a certain maximum pressure.

CONDITIONING PROCESS

During the conditioning process breakdowns and multipacting limit the power that can be accepted by the cavity. Outgassing and sparking significantly affects the vacuum

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ISBN 978-3-95450-169-4

performance and limits the RF field level that can be reached reliably. It is important to understand multipacting and breakdown phenomena in order to use them towards the purpose of RF conditioning. Here is a brief discussion of both:

Multipacting

Multipacting is a resonant RF electron discharge in vacuum. In the case of L4 cavities multipacting resonances appear at field levels around 1 to 10 kW. The secondary emission yield (SEY) of the oxide layer formed on the copper surfaces of the cavities, is higher than the one of a clean copper surface [5]. This enhances the multipacting activity. Triggering multipacting inside the cavities over long periods of time leads to a reduction of oxide in surface layers and lowers its emissivity to even lower values than in cleaned material [6]. This decreases significantly the multipacting and cleans inner surfaces of the cavity. For that reason, our strategy includes long periods of conditioning at multipacting field levels.

The accumulation of the electrons leaving the copper surface during multipacting changes the electrical characteristics of the cavity. Their periodical movement influences temporally the impedance matching with the power coupler of the cavity leading to a fluctuation in time of the power that enters the cavity. This periodic fluctuation is observable within the duration of one pulse. An example of a distorted pulse due to this process along with the vacuum levels during conditioning on the specific multipacting state is given in figure 1. The distortion of the pulse shape can be used to identify at which field levels multipacting occurs. When multipacting stops, there is no distortion, which serves as a criterium for evaluating the state of the conditioning process.

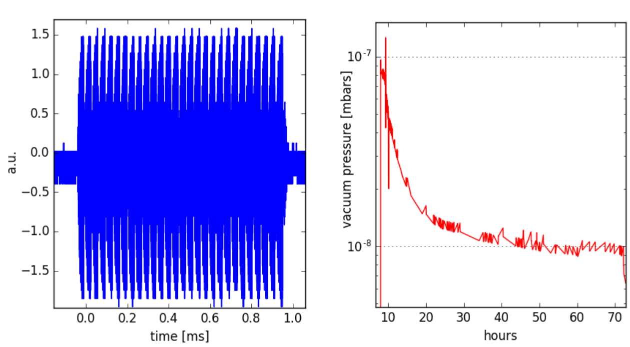

Figure 1: Field probe pulse signal (blue) and vacuum pressure (red) measurements during multipacting conditioning of a PIMS cavity (forward power 850 W)

Breakdowns

During the initial high power conditioning stage the breakdown rate and the vacuum pressure are high. The high breakdown rate is caused by outgassing products and surface contaminants in high field areas. After sufficient conditioning time the vacuum pressure and breakdown rate decrease. The necessary conditioning time to reach this point is different for every cavity type. After this stage, breakdowns continue to occur and they are mostly related to imperfections and dynamics of the metal surface [3]. This second stage of conditioning is also beneficial for the performance of the cavity as is evident from the gradual decrease in vacuum pressure. This double stage process cleans the cavity surface and allows reaching nominal levels in vacuum pressure and RF field level with a low breakdown rate.

A breakdown in the cavity is detected on the cavity feed as a temporary short circuit inside the cavity. The power to the cavity is fully reflected. By observing the field probe signals (fig. 2) one can identify the moments a breakdown occurred.

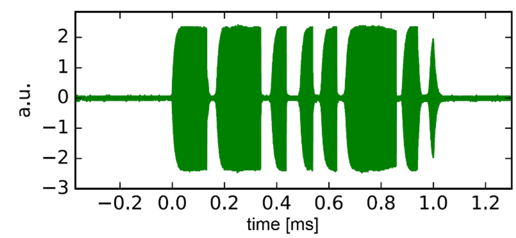

Figure 2: Field probe pulse signal during breakdown activity on a PIMS cavity (pulse trigger t = 0 ms)

RF Conditioning

The low level RF (LLRF) systems were still being installed and commissioned during the conditioning period. Thus an automatic conditioning system was not available at that time. For that reason the conditioning is being done in a manual way with frequent surveillance. In case of sudden increase of the vacuum pressure inside the cavity a vacuum interlock shuts the RF down when the pressure reaches $5 \cdot 10^{-6}$ mbars. The strategy with the main conditioning steps followed for the majority of the cavities is provided here:

1. Condition with RF pulses of 100 μs width and 100 W power (multipacting stage) with 1.2 s pulse repetition.
2. Gradually increase the pulse width up to 1 ms (maximum pulse width of the modulator).
3. Vary RF power in multipacting state until vacuum pressure has decreased and stabilized.
4. Increase RF power to a new multipacting level. Repeat this step until all multipacting levels that can be observed in low power have been conditioned.
5. Increase power gradually until breakdowns start. Condition to the highest power that can be reached without triggering the vacuum interlock too often.
6. Adjust the RF power to a higher level after vacuum pressure and breakdown rate have decreased. Repeat this step until nominal power plus 20 % is reached.

It is important to make sure that during conditioning the cavity is on tune. For the CCDTL cavities which are sensitive to temperature changes an automatic LLRF tuning loop is a prerequisite for conditioning. For the DTL and PIMS

ISBN 978-3-95450-169-4

cavities manual tuning is sufficient for conditioning. The conditioning with multipacting needs little surveillance as it does not involve sudden vacuum pressure bursts. For that reason and in order to optimize the available time, conditioning at multipacting levels was mostly done during nights and weekends.

The vacuum pressure and RF power measurements during the conditioning of a CCDTL cavity are shown in figure 3.

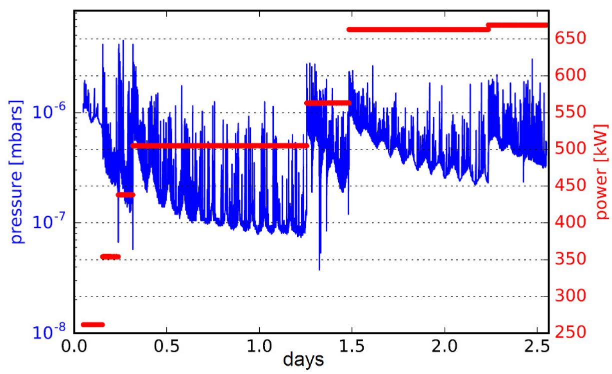

Figure 3: Development of the vacuum pressure over time during the conditioning of a CCDTL cavity (blue), power inside the cavity (red).

In Table 1 the average conditioning time for all structures is given along with the Kilpatrick limit. While the cavities are designed for 10% duty cycle, Linac4 is limited to 1.2 s repetition rate with 1 ms maximum pulse length. A higher repetition rate could have significantly reduced the conditioning time. Moreover an automatic conditioning routine, that re-adjusts RF power according to vacuum levels and breakdowns, would have significantly reduced the conditioning time. In general the CCDTL cavities were the most demanding in conditioning time as explained above. On the other hand the PIMS conditioning was much quicker.

Table 1: Conditioning Time and Kilpatrick Limit Values for the Different Cavity Types of Linac4

	DTL	CCDTL	PIMS
average conditioning time [days]	14	19	9
maximum surface field [Kilp.]	1.5 / 1.4 / 1.3	1.6-1.7	1.8

RESIDUAL GAS ANALYSIS

Residual Gas Analysis (RGA) is a spectrometric measurement technique by ionisation and mass separation of gas molecules in high vacuum. For accelerating cavities it is used to quantify the outgassing of contaminants on the cavity surface. The acceptance criteria for Linac4 cavities have been defined as follows: All masses between 18 and 44 amu should be at least 100 times lower than the intensity of the peak 18 (H_2O) except for masses 28 (N_2) and 44 (CO_2). All the masses from 44 to 100 should be at least 1000 times lower than the intensity of the peak 18 except for mass 44. The RGA results before and after conditioning of a CCDTL cavity are presented in fig. 4. The RGA before conditioning did not fulfil the criteria. The presence of oil contaminants with typical masses of 39, 41, 43, 53, 57 and heavy hydrocarbons at the region above 44 amu is revealed by the RGA plot. Nevertheless, after conditioning the RGA shows significant reduction of contaminants. The ion current values are normalised for both cases to the peak of the water (18 amu) for a qualitative comparison as the absolute pressure levels might vary with the vacuum system and pumping speed.

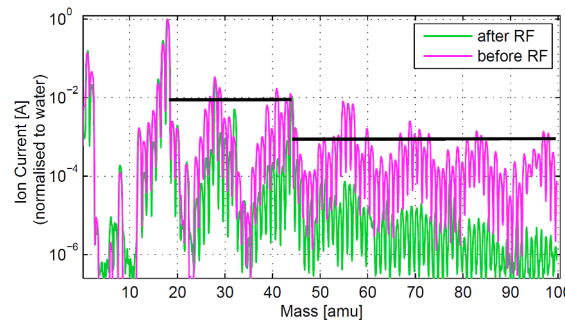

Figure 4: RGA analysis of a CCDTL cavity before and after conditioning. The black lines indicate the acceptance limits.

In the assembly process of the DTL and PIMS cavities all parts have been cleaned mostly at CERN workshops and the RGA results before conditioning show that they have stayed clean in the assembly process and did not suffer from contaminations. Most PIMS cavities have passed the RGA tests even before conditioning. In CCDTL cavities oil and hydrocarbon contaminations have been observed that could not be cleaned in later assembly stages.

In order to ensure that vacuum levels are appropriate for machine operation, RGA measurements have also been performed after the conditioning stage. Independent of the starting level, all RGA measurements show that after conditioning, contamination has decreased to acceptable levels.

CONCLUSIONS

All 3 Linac4 cavity types were successfully high-power conditioned. Conditioning times vary according to structure type and the level of surface contamination. After conditioning the surfaces of all cavities are sufficiently clean to pass the acceptance criteria for connection to the beam vacuum.

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ISBN 978-3-95450-169-4

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