188th Meeting of the Machine Protection Panel
Special meeting on LINAC4 RFQ protection

The meeting took place on **May 6th 2020** via Zoom.

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The slides of all presentations can be found on the website of the Machine Protection Panel and on Indico. These minutes include a summary of 1) the findings and proposals, 2) the discussion, as well as 3) the assessment and recommendations for each of the presented topics.

1 Findings on Linac4 RFQ vane damage and proposed mitigation strategies (Richard Scrivens)

1.1 Findings and proposals

- **Breakdown craters, scratches and so-called worm-like features have been observed** on the Linac4 RFQ vanes by visual inspection using endoscopes and high-resolution cameras.
- Similar breakdown craters and worm-like features were also observed at the CLIC high-field structures and at the Linac2 RFQ.
- Contrary to the initial interpretation of the endoscopic images, **no material removal or peel-off** was noticed in the high-resolution images. Instead, a local modification of the vane surface seems to cause zones of different surface roughness and, thus, reflectance.
- **No significant degradation of the beam and RF performance** have been detected for the Linac4 RFQ so far.
- The achievable resolution during the visual inspection did not allow to conclude on the occurrence of blistering inside the RFQ. However, blistering was confirmed at a copper mask that was irradiated for 24 hours at the Linac4 test stand with approximately 1e19 H^- ions. The latter corresponds to ~1% of the expected annual number of protons from Linac4.
- Consequently, **blistering is expected to occur also at the RFQ vanes** in case of H^- beam impact. The main worry is that the blistering zones become seeds for future RF breakdowns. Therefore, beam losses inside the RFQ should be minimized.
- Based on the observed findings and given the criticality of the RFQ to the availability of the CERN accelerator complex, a **spare RFQ is an important risk mitigation** and a corresponding project has been launched.
- Since the spare RFQ will not be available before mid-2022, the **present RFQ has to be protected while maintaining routine operation**.

- The **RFQ protection strategy** relies on:
  - Limiting the RFQ output current to 25 mA
  - Controlling the RF breakdowns to limit the surface modifications
  - Avoiding unnecessary beam losses inside the RFQ
- To reduce the beam losses inside the RFQ, the installation of a fixed copper mask upstream the RFQ was studied. The study revealed that the mask only provides efficient additional protection for the failure case of an under-focused beam (e.g. caused by incorrect solenoid settings), but not against mis-steered beam or against routine losses during nominal operation.
- Therefore, it was **decided not to install a mask** but to improve the **management and protection of the LEBT settings**.

1.2 Discussion

- A. Lombardi commented that the goal is to achieve the required RFQ output current of 25 mA with the **lowest possible source current**, such that the losses inside the RFQ are minimized.
- C. Wiesner asked how the **Linac4 RFQ compares to other RFQs** in terms of field level or Kilpatrick factor. Richard answered that the Kilpatrick factor for the Linac2 RFQ is actually higher than for the Linac4 RFQ. However, significant less cratering is visible at Linac2, which might be an effect of the different vane material. He added that similar surface modifications were observed at the SNS RFQ, which is made from pure copper.
- C. Hernalsteens asked how much time would be required to **replace the RFQ**. R. Wegner estimated one to two months for the entire process. R. Scrivens added that this number would be re-assessed within the new RFQ spare project.

1.3 Assessment and recommendations

- Based on the presentation given, the MPP concluded that it is **not confirmed that the LINAC4 RFQ is having more important surface problems** than other RFQs in operation
- The MPP highlights the **key importance of the Linac4 RFQ for the availability** of the whole CERN proton accelerator chain, in particular, as long as no spare RFQ is available. Therefore, an **optimized RFQ protection strategy** is considered essential to ensure the availability of the accelerator complex.
- The MPP **supports the proposed general Linac4 RFQ protection strategy** of a) increasing the RF breakdown protection, and b) minimizing the beam losses inside the RFQ by an improved LEBT settings management as well as by keeping the 25 mA limit on the RFQ output current.

2 Strategy for RF breakdown protection of the Linac4 RFQ (Rolf Wegner)

2.1 Findings and Proposals

- The **current protection of the RFQ** consists of interlocks on the vacuum level, klystron and modulator.
- In case of an RF breakdown, the LLRF tries to stabilise the voltage by increasing the RF power, thus, increasing the damage potential to the RFQ surface. Due to the large installed pumping speed at the RFQ along with the gas flow from the upstream source and LEBT, the vacuum interlock is usually not triggered during an RF breakdown.
- Therefore, additional protection is required to limit the number and consequences of RF breakdowns in the RFQ.

- The following **additional protection against breakdowns** is proposed:
  - If the reflected power exceeds an adjustable threshold level, a fast (~50 µs) interlock is generated inside the RF control system.
  - The interlock a) removes the RF pulse permit and b) sets the RFQ user permit to the SOURCE BIC to FALSE, thus, inhibiting the beam.
  - For a single breakdown, the interlock is auto-reset before the next pulse, re-establishing the RF and the beam permit.
  - For breakdown clusters (3 breakdowns within a moving window of 25 pulses) or a high breakdown rate (8 breakdowns within a moving window of 9000 pulses), the interlock latches and an RF recovery has to be initiated.
  - During the recovery process, the RF pulse permit has to be re-enabled while the RFQ user permit to the BIS has to remain FALSE to keep inhibiting the beam.
  - Therefore, the current link between the RF pulse permit and the RFQ user permit has to be modified by adding an AND gate on top of the present logic.
  - Depending on the number of breakdowns, different recovery levels with reduced voltage amplitude and increased recovery time are foreseen (R. Wegner, slide 8). If the number of breakdowns exceeds a certain thresholds, the RFQ will go to a locked state, which requires an expert intervention.
  - For better traceability, alarms will be generated for all interlocks, and all diagnostics will be made available in the control room.

2.2 Discussion

- D. Wollmann asked how the **allowed numbers of breakdowns** have been defined. R. Wegner replied that they are based on the experience with the CLIC high-field structures, and had to be adapted to the lower repetition rate and longer pulse length at Linac4. During normal operation a breakdown rate of 1e-5 is expected and assumed to be the best compromise between performance, protection and availability. A breakdown rate of 1e-3 is too high and requires action to recover performance. He added that these numbers would be revised based on the operational experience after the restart.
- Replying to a question by D. Nisbet, R. Wegner explained that around **500 breakdowns were observed during the LBE run**. However, the real number is expected to be higher due to the not fully efficient logging system, which will be improved for the next run.
- B. Mikulec stressed that the protection functionality relies on the correct detection of the breakdowns and asked if a **redundant detection system** is foreseen. S. Ramberger replied that the detection of the reflected power is a well-established method and that the RFQ is already protected against very strong breakdowns by the vacuum interlock. The new interlock adds an additional protection layer. Therefore, he believes that no redundancy in the detection system is required. Rolf added that the modulator interlock would trigger if the klystron requested too much power, and that the watchdog would interlock, if the beam transmission drops below the defined threshold.
- R. Steerenberg asked how the new protection system would affect the **RFQ availability**, given that, on the one hand, the number of breakdowns is expected to decrease, while, on the other hand, additional time is required for the RF recovery. R. Wegner answered that this has to be evaluated after the first operational experience. He added that a decreased number of RF breakdowns would also reduce the number of bad pulses with insufficient beam quality.

2.3 Assessment and recommendations

- The findings indicate that the observed RFQ vane modifications are mostly caused by RF breakdowns, and less by direct beam impact. Therefore, the **additional RF-internal protection based on the reflected power to reduce the number and severity of RF breakdown is considered an important additional protection layer**, which should be implemented before the Linac4 re-start.
- The **decoupling of RF and beam interlocking** is considered a clean and consistent solution. It allows to reliably inhibit the beam via the BIS while the RFQ is in recovery mode without requiring additional software layers.
- The MPP recommends to implement the **hardware connection for breakdown detection** (reflected power measurement) and to implement the **RF controls changes to decouple RF pulse and RFQ BIS user permit**. After the implementation, a full re-validation of the modified system has to be performed.
- Action (R. Wegner/BE-RF): Evaluate RF interlocking and recovery procedure based on the experience from the Linac4 commissioning and early operation and report the results to the MPP.

3 Software implementation for RF breakdown protection and recovery (Bartosz Bielawski)

3.1 Findings and proposals

- In order to implement the breakdown-protection strategy discussed above, a **new software system** is required that
  - distinguishes between single breakdowns and breakdown clusters/high breakdown rate,
  - initiates an automatic RF recovery procedure for breakdown clusters/high breakdown rate,
  - provides reliable information about the RFQ breakdown rate.
- The new software structure is based on a FESA device (“BreakdownRecovery”) with two main properties: a command property to request the state transition and a status property to return the current/suggested state.
- The proposed implementation requires **modifications to the RF control system**, including:
  - new connections for the reflected power measurement and interlock,
  - update of the interlock PLC class with additional software inputs (“RF not ready” state),
  - update of the RF Sequencer with the new BreakdownRecovery class.
- The parameters of the RF recovery ramps will be a configurable expert property in the code.
- Information as the FESA class state, expected recovery time, and breakdown rate, will be accessible via an inspector panel in the control room. Alarms about the RF status will be sent via LASER.

3.2 Discussion

- C. Wiesner asked if the **beam stopper**, which would allow restarting the ion source, would be inserted automatically or manually. Richard replied that an automatic insertion would be beneficial for availability and could be implemented via the SIS. B. Mikulec remarked that both options are still being evaluated. J. Uythoven commented that an automatic insertion would be feasible, however, an automatic removal might lead to an undesirably large number of stopper movements. D. Nisbet stressed that the key point for operation is that the information about the RF status is clearly available in the control room.

- D. Wollmann asked if the **reliability of the RF-BIS connection** would be altered by the proposed modification. B. Bielawski replied that the functionality of the existing RF interlocks would not be affected. He added that in case of a failure of the new software layer, the hardware protection would remain active.

3.3 Assessment and recommendations

- The **automatic removal of the beam stopper** following the breakdown recovery should only be implemented after careful evaluation, based on the operational experience and considering the effect on the lifetime and criticality of the beam stopper.
- The detailed **testing and revalidation of the new software system** is required to ensure that the functionality of the existing RF internal interlocks and the reliable connection to the BIS is not impacted by the modifications.

4 Management and protection of Linac4 LEBT settings (Richard Scrivens)

4.1 Findings and proposals

- The **transmission through the Linac4 RFQ**, as measured from the LEBT BCT to the first MEBT BCT, is currently ~70%. Beam losses inside the RFQ are, thus, expected during routine operation, but unnecessary increases in losses for extended periods have to be avoided.
- The RFQ transmission is strongly dependent on the **LEBT settings**. Therefore, an effective management of these settings is required to limit the RFQ losses.
- The proposed *Logic for SIS Software Verification of LEBT Parameters* will be specified in EDMS L4-CIB-ES-0007. It comprises the monitoring and interlocking of, amongst others, the LEBT solenoid, steerer, and einzel lens settings.
- **Three operational modes** with different LEBT protection settings are foreseen:
  - Mode 1: **Standard operation**: tight settings around nominal central values.
  - Mode 2: **Low transmission mode**: tight settings around modified central values. For this mode, the RFQ output current has to be reduced to 7-8 mA for the (occasional) RF re-phasing of the linac by changing the solenoid focussing. However, the losses inside the RFQ have to be minimized by ensuring the correct solenoid settings and by reducing the beam pulse length.
  - Mode 3: **Machine Development (MD) mode**: settings to be defined for the specific MD.
- The operational mode and the min/max settings for all three modes (slides 10-12) will be stored as **LSA machine critical settings** and are **protected via RBAC** ("Linac supervisors").
- The device acquisitions will be compared to the above-mentioned min/max limits by the SIS. If at least one value is out of range or false, a **bad pulse counter** is increased. If the bad pulse counter exceeds the defined threshold, the **SIS input to the Choppers BIC** latches to FALSE and the beam will be stopped via the BIS. The interlock can be reset by the operators (no specific RBAC role required). After a mode change, the counters will be automatically reset.
- In addition, a **lifetime counter** will latch the SIS input to the Choppers BIC to FALSE if a mode-dependent maximum number of pulses is exceeded, e.g. 3000 pulses (~1 hour) for Modes 2 or 3.

- The tolerance windows for Modes 1 and 2 are considered critical and changes to them should be documented in the specifications, while the central reference values can be changed by the Linac4 supervisors.

4.2 Discussion

- B. Mikulec commented that the **cavity re-phasing**, which requires Mode 2, takes considerably longer than the foreseen 1 hour. She asked whether the value for the **lifetime counter** should be increased. G. Arduini and R. Steerenberg commented that the lifetime counter should be kept as short as possible. R. Scrivens added that, if the lifetime counter is exceeded, only the beam would be blocked until a manual reset. He confirmed that **no automatic mode change would be performed**. B. Mikulec replied that, in this case, the 1 hour value would be acceptable. R. Steerenberg added that a **countdown timer** for the mode lifetime should be published in the control room.
- B. Mikulec commented that currently a **sequencer task for switching to the low-intensity mode** is under preparation by OP (EDMS L4-C-PRD-0001). This task includes the setting of the solenoid values and of the maximum pulse length (tailclipperTime_Mode2_Max), which are also set in the new SIS application. Richard commented that the maximum pulse length required for this mode should not be changed. Concerning the solenoid and steerer settings, he commented that storing the values in two separate places increases the protection against accidentally putting the wrong settings. B. Mikulec replied that also the sequence of steps, e.g. when the pulse length is set, has to be reviewed. R. Steerenberg remarked that the cleanest solution would be to have a single parameter that is stored in LSA and protected via RBAC. D. Nisbet and D. Wollmann commented that, in general, protection settings and controls settings should be stored separately.
- C. Wiesner asked how **MDs at Linac4** are approved. R. Scrivens explained that all critical MDs that require the settings held in this system to be modified to values outside the operation ones have to be presented and approved in the Linac4 supervisor meeting, but usually no written procedure is required. It is the responsibility of the Linac4 supervisor to ensure the correct change of settings for the MD.
- C. Wiesner asked how the **space-charge compensation in the LEBT** affects the beam size at the RFQ entrance and how it is monitored during operation. R. Scrivens replied that the compensation degree is indirectly monitored by the pressure measurement in the LEBT and by beam losses in the RFQ. He confirmed that a changing space-charge compensation would indeed increase the losses and should therefore be reviewed after some operational experience.

4.3 Assessment and recommendations

- The **SIS connection** to the Choppers BIC, and not to the Source BIC, is used. This minimizes the impact on the Linac4 ion source, which can keep pulsing. However, it implies that a single actuator (pre-chopper) upstream the RFQ is used to cut the beam, and not two independent actuators. This is deemed acceptable considering that the pre-chopper functionality is independently interlocked and that no fast action is required. However, **for long-term operation this situation should be re-assessed** with MPP.
- The defined maximum **lifetime for the non-nominal operation modes** should be kept short, around one hour, and the status of the lifetime counter should be clearly displayed in the control room.
- Since the **LEBT settings protection in MD mode** (Mode 3) relies mainly on procedures, a careful preparation, discussion and supervision of machine-protection critical MDs is required.
- Action (B. Mikulec/BE-OP, R. Scrivens/BE-ABP): Review the specifications for the Linac4 sequencer task for switching to the low-intensity mode (EDMS L4-C-PRD-0001) in order to ensure coherence with the new “Logic for SIS Software Verification of LEBT Parameters” (EDMS L4-CIB-ES-0007).

- Action (B. Mikulec/BE-OP, R. Scrivens/BE-ABP): Clarify if the central values of LEBT settings should be stored as LSA virtual parameter to allow them to be read out by the foreseen sequencer task, taking into account the experience of similar applications in the injectors.

5 Interlocking and SIS implementation of Linac4 LEBT settings (Tibor Bukovics)

5.1 Findings and proposals

- The proposed **implementation for the LEBT settings management system** is based on a **software architecture that combines SIS and UCAP** (Unified Controls Acquisition and Processing Framework).
- The more complex analysis will be performed in UCAP, while the SIS is required for handling the logical decision tree, as well as masking, latching, and communicating the beam permit.
- The UCAP configuration will be protected via RBAC.
- UCAP is already used for the Linac4 autopilot, but has not been used so far in combination with the SIS.
- If the UCAP node stops accidentally or the UCAP converter stops publishing, the SIS would consider this a failure condition and stop the beam via the BIS.
- In total, a system reaction time of up to a few seconds is expected, similar to a pure SIS solution.

5.2 Discussion

- M. Buttner agreed that using UCAP together with SIS has advantages in terms of code writing, testing and maintaining, and could, thus, help to increase the reliability of the system.
- J. Wenninger asked if the UCAP layer is incorporated into the SIS server. M. Buttner explained that this is not the case and that UCAP and SIS are hosted on different servers.
- J. Wenninger commented that by using UCAP one clearly adds an extra software layer, but a similar approach is used at LHC in the form of concentrators. He added that this is a design choice, and one should choose the most flexible and maintainable solution.

5.3 Assessment and recommendations

- Special attention should be paid to the fail-safe implementation of the UCAP-SIS layer, which has to be tested and validated accordingly, and to the operational reliability of the UCAP services.

6 Concluding remarks

- J. Uythoven thanked all the speakers for their very clear presentations and the thorough preparation. He remarked that the presented protection and interlock strategy looks appropriate and announced that more detailed assessments and recommendations would be sent out together with the MPP minutes.
- R. Scrivens thanked the MPP members for their support and suggestions and remarked that it has been a very beneficial process to come to the MPP.