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This document includes 12 pages with an executive summary at the end, and is accompanied by 5 appendices in a separate file (appendix.pdf)

The authors of this report were invited to review the H⁻ ion source program at CERN. The review was conducted on February 4-5th, in which CERN staff gave 11 high-quality presentations on the objectives, status and outlook of the injector (H⁻ ion source, LEBT and transmission through the RFQ) development. On February 5th, the four authors discussed the presentations and formulated a preliminary report that was presented to the CERN staff during the close out session. This document (and its appendices) is a follow-up on the preliminary report of February 5th.

The reviewers were asked to consider two main themes:

1. The review should assess the readiness for 24/7 operation that will start in mid 2020.
   - Has the progress since the last review been sufficient and have the previous review recommendations been taken into account?
   - Is the source ready in terms of operation, spares and failure recovery preparation? Have the right methods for operation been chosen?
   - Can any further improvements be proposed?

2. For the development of the source and low energy stage with an objective to reach 45mA reliably out of the RFQ in 2023, after demonstration on the test stand in 2022.
   - Has the progress since the last review been sufficient and have the previous review recommendations been taken into account?
   - What is the likelihood to reach 45mA out of the RFQ?
   - Is the plan and schedule for the future clear, with sufficient detail, and is it sound?
   - Are the relevant issues addressed?
   - Are the resources adequate?
   - Can any further improvements be proposed?
The purpose of the Linac4 accelerator, under commissioning at CERN, is to increase the injection energy of the PSB accelerator and, thus the luminosity of the LHC. This can be accomplished with 25 mA out of the RFQ. The 45 mA requirement (after 2023) is mainly driven by increasing the intensity to the nuclear physics program at CERN, but the reviewers understand this is not part of the present baseline program at CERN. Connecting Linac4 to PSB marks a paradigm shift how CERN operates as it will be the first time H⁻ beam is used instead of a proton beam to inject particles into the CERN accelerator chain.

The H⁻ ion source development at CERN has resulted in a caesiated RF ion source being the technology of choice for Linac4. The reviewers are impressed by the results of the CERN ion source program and the demonstrated progress in the 15 months since the previous review. The progress has been sufficient in terms of the ion source operation at 25 mA. Successful examples include adopting continuous caesiation as a baseline operation mode, implementing the evolution version of the autopilot, decision to use the cusp-free version of the ions source, insights gained in the beam optics and improvements of the 2 MHz RF system. These achievements have significantly improved the stability and reproducibility of the ion source performance. We conclude that the previous recommendations of the 2018 review have been mostly taken into account with minor exceptions (see Appendix A for details).

The committee concludes that the RF ion source using continuous caesiation and equipped with autopilot appears to be ready for Linac4 operation with 25 mA out of the RFQ at 1.2 s repetition rate (with the specified pulse flatness and reproducibility as well as source availability). At the time of the review spare sources were not ready. The committee recommends expediting the production and qualification of the spare sources on the ion source tests stand. In practice this means that two sources should be prepared before mid-June to allow them to be qualified on the test stand in June-July 2020 (subject to delays due to evolving SARS-CoV-2 / COVID-19 pandemic). The qualification runs should have a high priority as already shown in the test stand schedule presented to the review panel. However, the committee is concerned that the initially allocated 3 week period for qualifying two spare sources is by far not enough. The committee recommends allocating 4 weeks for each source, which allows to monitor long-term effects, e.g. change of the e/H⁻ -ratio, and identify possible discrepancies between the sources intended for operation. Four weeks tests should allow enough time for operational issues to emerge and be resolved with no incursion of accelerator downtime. These qualification runs should be performed maintaining the beam current (measured from the RFQ mask) at the level corresponding to 25 mA out of the RFQ in the Linac4 tunnel. The qualification runs should essentially replicate the conditions and performance goals of the 24/7 operation. Operational
experience from other facilities suggests that all sources (spares) do not reach the same performance despite of seemingly identical components and handling procedures. CERN should be prepared to similar findings.

Following the example of other operational facilities (SNS, J-PARC and ISIS) the spares need to be defined as discrete ion sources with specific (to each source) selection of well-documented identical components having detailed handling/cleaning procedures. It is recommended that each spare source is equipped with identical caesium delivery system i.e. oven and transfer line at least until the proposed upgrade (see below) has been designed and qualified. Components of the Cs delivery system should also be kept in the inventory of spare parts as this subsystem creates a possible (yet unlikely) failure mechanism that could be addressed without changing the ion source itself. A clear written start-up procedure of the ion sources must be developed. All local experts must be involved in the process and acknowledge the outcome. The final procedure should also allow fast recovery from failure and needs to be first implemented on the test stand. The refurbishment and start-up procedures adopted at different facilities are described in Appendix C-E (or references therein). It is emphasized that other facilities operate with different repetition rates, duty factors and even source technologies. It is therefore important that CERN develops their own strategy and implements it as soon as possible.

The written operational procedure should include an upper threshold for the e/H⁻-ratio that requires a human intervention (maintaining 25 mA out of the RFQ). The committee sees manual caesium oven control to be the best option at this time for mitigating the long-term increase of the e/H⁻-ratio. Implementing the caesium oven temperature control into the autopilot is recommended later when operational knowledge has been acquired in the Linac4 tunnel and at the test stand.

The machine protection should be implemented in two stages – (a) first switching off the ion source extraction high voltages and keeping the RF on the preserve ion source discharge conditions and (b) only if absolutely required switching of the RF power.

The committee makes the following further recommendations relevant for the ion source operation at the 25 mA beam current out of the RFQ. All technical solutions should be first tested on the ion source test stand and the clearly successful ones should be later implemented in the Linac4 tunnel.

- Monitoring (and later controlling) the plasma electrode temperature should be implemented.
- Upgrading the caesium delivery system with higher conductance valve technology should be investigated. This would help pumping out the impurities from the Cs reservoir, which is seen essential for long-term stability, e.g. maintaining a favorable e/H⁻-ratio.
- Operating the caesium transfer line at constant elevated temperature and only varying the oven temperature should be implemented. This would presumably allow a faster Cs response.

- Monitoring the caesium and impurity element levels in the discharge chamber through photometry and/or residual gas analysis should be considered.

- The solid state RF system should be gradually implemented eventually keeping the existing tube-based amplifier as a spare.

The committee views the ion source test to be sufficient for testing the above techniques / technologies relevant for 24/7 operation at 25 mA current. However, at this time the apparent discrepancy between the results obtained at the test stand (beam current through the RFQ mask) and in the tunnel (beam current through the RFQ) does not warrant qualifying the ion source performance at currents above 30 mA using the test stand. It is of high importance to understand the root-cause of the differences between the tunnel and the test stand. This is especially important for the goal of reaching 45 mA out of the RFQ by 2023.

The second part of the review charge is dedicated to the development of the source and low energy stage with an objective to reach 45 mA reliably out of the RFQ in 2023, after demonstration on the test stand in 2022. The plan to reach 45 mA by 2023 was based on the possibility to evaluate the performance of the source/LEBT at the test stand relying on the so called RFQ mask. At this time it is unclear how the demonstration can be carried out as there is an apparent discrepancy between the transmission measured with the RFQ mask on the test stand and the true transmission through the RFQ. The beam current out of the RFQ reaches 32 mA as a maximum and then decreases when the current out of the ion source is increased beyond 40 - 50 mA. The decrease of the transmission is pronounced in the tunnel in comparison to the RFQ mask at the test stand. The increase of the transverse emittance at beam currents exceeding 40 mA is the most probable cause for the reduced transmission. CERN is actively studying possible origins of the discrepancies, in particular the possible misalignment of the source – LEBT- RFQ.

It is therefore concluded that the plan for reaching 45 mA is not clear and, thus, the likelihood to reach 45 mA out of the RFQ in 2023 appears very low given the data presented to the review panel. It is especially worrying that there is no time allocated for high current tests with the RFQ. It must be established through a systematic investigation whether the ion source and its beam optics or the RFQ is the key problem. This should be urgently addressed as it is a key to 45 mA operations by 2023. Emittance measurements with optimized extraction electrode potentials for each extracted current are highly valuable and should be pursued at the test stand to gain more insight into the beam optics and...
to clearly establish if the source operates in under- or over-perveant regime. In the under-perveant range the extraction voltage is too high for a given current resulting in strongly concave meniscus, which deeply intrudes into the plasma. In the over-perveant range the extraction voltage is too low for a given current and the plasma meniscus can approach a flat or even convex shape. For optimum perveance, i.e. in-between the under- or over-perveant range, the divergence of the extracted particles is at its minimum, thus minimizing the transverse emittance. It is acknowledged that the electron dumping scheme limits the adjustment range of the extraction voltage. Nevertheless, the extraction voltage should be optimized for each beam current (plasma density). This needs to be done experimentally as the plasma model used in IBSimu is a simplification of the actual physics and the plasma meniscus is affected by the H⁺ production mechanism (volume and surface). The beam emission spectroscopy experiments (preliminary results presented in the review) can help in gaining insight on this matter although it must be emphasized that the interpretation of the results must be done carefully as the experiments are carried out in residual gas pressures greatly exceeding the nominal operational conditions.

*It is recommended to consider moving the emittance scanner to the end of the beamline at the test stand, i.e. replacing the RFQ mask with the scanner, and comparing the measured transverse emittance to the RFQ acceptance at different beam currents.* We believe that relocating the proven emittance scanner to the theoretical RFQ entrance aperture position on the test stand would give better characterization of the candidate sources and extraction systems. These data could then be compared directly to PARMTEQ acceptance simulations of the RFQ performed at relevant beam currents giving much better estimates of RFQ transmission and the expected 3 MeV beam current. It is recommended to first (while qualifying the spare sources) carry out a feasibility study addressing the technical issues related to the possible relocation of the emittance scanner and weigh the foreseen benefits against the drawbacks including required manpower. As an alternative CERN should investigate if an emittance scanner(s) can be loaned to do this. Relocating the emittance scanners becomes increasingly valuable if the discrepancy between the RFQ mask and RFQ transmissions remains not well understood i.e. beams traced forward from the present location of the emittance measurement do not match the measured RFQ transmission.

The predicted beam transport efficiency through the RFQ seems relatively low. In order to identify the root cause of the poor RFQ transmission at high injected beam current it is recommended to measure the RFQ transmission as a function of the injected beam energy, confirm with bremsstrahlung end-point energy measurement that the RFQ reaches the expected electric field (peak) strength, and measure the flatness of the beam pulses in the beam current regime (> 40 mA from the
source) where the RFQ transmission deviates from the RFQ mask transmission. The RFQ mask acceptance corresponds to the zero-current acceptance of the RFQ. It is recommended that CERN considers changing the mask acceptance to correspond to the best estimate of the RFQ acceptance at 50 – 70 mA injected current, and investigating the transmission into the mask at this setting. The highest beam current transported through the RFQ mask has been achieved with a 9 mm plasma electrode aperture, supported by emittance measurements indicating that the transverse emittance increase at high beam currents can be shifted to higher currents by opening the extraction aperture diameter. In this light it is not fully clear to the review panelists why the 7.5 mm aperture for which the emittance increase occurs at lower beam current has been chosen for the “baseline source” installed in the tunnel. This choice is presumably driven by the operational experience with the 7.5 mm aperture and by the desire to protect the RFQ from excessive beam losses within the accelerating structure. Keeping in mind that the initial goal is to reach 25 mA out of the RFQ, this choice appears to be adequate. Nevertheless, we encourage CERN to continue experiments (where and when possible) with those extraction systems that have shown to produce smaller emittance values at high currents. In these experiments it is important to optimize the extraction electrode potentials for smallest possible emittance and/or best RFQ transmission. Finally, it is understood that particle distributions reconstructed from the emittance measurements are used to predict the RFQ transmission at different beam currents. However, it is unknown what particle distribution (e.g. KV or water-bag distribution) was assumed for the RFQ design in the first place and how representative of the actual beam properties the design distribution is. We therefore recommend CERN to review the RFQ design to assess whether the real-world particle distribution results in insufficient longitudinal focusing or if the poor transmission at 50 – 70 mA LEBT current is solely due to large transverse emittance of the beam.

The review panelists noted that the RFQ transmission studies were conducted by varying the beam current by changing the 2 MHz RF power sustaining the ion source plasma and then optimizing the solenoid focusing and steering for maximum RFQ transmission. However, the extraction electrode voltages were not adjusted separately for each setting. Optimizing the extraction electrode voltages is important as they affect the beam formation and could mitigate the transverse emittance growth. Thus, it is recommended that CERN revisits the RFQ transmission (beam out of the RFQ) as a function of the LEBT (ion source) current optimizing the extraction electrode voltages for each beam current. This experiment has a high priority as it could potentially help reaching 45 mA out of the RFQ or at least guide further development of the extraction system by revealing whether the beam optics is the root cause for the observed discrepancy between the test stand (RFQ mask) and tunnel
(actual RFQ) transmission at high current. The experiment should be complemented by emittance measurements at various beam currents with optimized electrode voltages at the test stand.

When the root cause for poor transmission is found CERN should organize a further review particularly addressing the 45 mA goal. The review should be scheduled with enough time between the review and the planned start of 45 mA operation in 2023 to make recommendations about the beam optics or the RFQ, for example.

_The committee strongly supports the implementation of the working group for the RFQ investigation._ In addition to assessing extent of the observed surface damage and its implications (operational, protective measures etc.), this “task force” should provide insight into whether the poor transmission is due to mismatch of the injected beam (too large emittance) into the RFQ or if the RFQ itself is at fault and requires re-characterization and re-tuning. _In the longer term, the ion source review panel recommends CERN to acquire another RFQ and associated test stand, and allocating enough resources, i.e. funding and manpower, to operate the test stand with the main purpose of qualifying operational sources for long-term operation and increasing the beam current out of the RFQ._ Based on the experience of other laboratories the availability of an RFQ test stand is vital for such a development. The RFQ represents a potential single point failure in the whole LHC chain with significant downtime, which needs to be addressed urgently. The above RFQ working group should give recommendations whether the new (spare) RFQ should be built following the existing RFQ design or if it was advisable to redesign the RFQ with larger acceptance to accommodate larger emittance from the ion source. The working group should compare the CERN RFQ design to those of other operational facilities utilizing the expertise available elsewhere. _Commissioning of the RFQ test stand with improved beam optics of the ion source (new high current extraction system) by the end of 2022 is seen as the only viable solution to achieve 45 mA out of the RFQ by 2023._ However, it is acknowledged that completing such effort is typically a long 5-10 year process and, therefore, most likely outside of the 3 year time horizon for the 45 mA / 2023 goal. The goal of reaching a current of 45 mA might be delayed if the RFQ transmission studies and review will evidence the need of a new RFQ design. The impact for CERN of delaying such an intensity was not discussed at the review.

Following the examples of J-PARC and SNS we recommend a dedicated ion source test stand (separate from the RFQ test stand). Test stands dedicated to RFQ and ion source development have been shown to be critical to long-term operations. The ion source test stand best serves the purpose of supporting multiple short-term tests and conditioning of spare sources.
As stated in the 2018 review final report, there are no fundamental reasons prohibiting to reach the 45 mA goal with the external antenna RF source – J-PARC and SNS operating internal (for accelerator operations) and external antenna RF ion sources and producing > 45 mA H⁻ current out of an RFQ are prime examples. In particular, if the J-PARC extraction and possibly a shorter LEBT was eventually adopted by CERN, the space-charge limited current of approximately 60 mA at 45 keV could be expected as J-PARC has demonstrated 66 mA, 80 mA and 100 mA at 50 keV, 56 keV and 62 keV, respectively.

While the short-term focus of the CERN ion source team should be in qualifying operational sources (spares) for 25 mA operation and establishing their start-up and handling procedure, it is evident that for 45 mA operation there is a need for an extraction system capable of handling high current of ions and electrons. The 2018 review recommended CERN to investigate the extraction systems of the J-PARC and SNS sources to guide the development. Simulation results of the J-PARC-type extraction system were presented to the 2020 review panel, indicating that 45 mA out of the RFQ could be reached with 75 mA (demonstrated earlier) out of the source thanks to smaller transverse emittance even at the predicted 60 % RFQ transmission. The J-PARC extraction operates by removing the co-extracted electrons at approximately 10 keV energy and then accelerating the beam to the final energy into the magnetic LEBT. In particular, in the J-PARC extraction system there is no electrostatic focusing (einzel lens) whereas the current CERN extraction has one, which seems to contribute to the transverse emittance growth suppressing the current out of the RFQ at high extracted currents.

A proposed new extraction system for the CERN source was presented to the review panel. The system relies on a two-stage scheme accelerating the beam (H⁻ and co-extracted electrons) up to 30 keV energy in the first acceleration gap and removing the co-extracted electrons at the final 45 keV energy by spreading them onto the surface of dedicated (biased) electron dump. The simulation results presented to the reviewers suggest that the proposed extraction system could deliver 45 mA through the RFQ with approximately 60 mA extracted from the ion source, which is encouraging. However, at 60 mA extracted H⁻ current it is predicted that 20-30% of the co-extracted electrons intercept the tip of the puller electrode, which creates a significant thermal management and problem. The BNL magnetron-type H⁻ ion source serves as an example of co-extracted electrons damaging the tip of the puller electrode. The thermal design of the presented system relies on the e/H⁻-ratio being very low (1-2 used in the simulations) whereas the operational values typical for the 25 mA long-term operation have been observed to be up to 10, increasing gradually with time. It is unclear what the maximum tolerable e/H⁻-ratio of the proposed extraction system is but it should definitely be designed based on the e/H⁻-ratio observed experimentally leaving appropriate engineering (e.g. thermal) margin.
Furthermore, it is unclear how the higher e/H\textsuperscript{-} -ratio would affect the transverse emittance of the beam. Finally, it would be essential to carry out a sensitivity study of the IBSimu input parameters potentially affecting the design of the new extraction system. In particular, it should be ensured that the same IBSimu input parameters that best reproduce the observations in volume operation mode are used for designing the extraction system (followed by later validation is surface production dominated mode) and that the results are not critically sensitive to the chosen set of input parameters. Altogether, it is concluded that the presented extraction design carries an elevated risk. For the above reasons the committee recommends a further systematic comparison of the already proven J-PARC and proposed CERN extraction systems including a sensitivity analysis of the simulation parameters (of IBSimu) before the decision to implement one of them on the ion source test stand is taken. Regardless of the actual extraction design, using graphite as an electron dump (electrode) material is strongly discouraged as it easily releases particles, which may influence the work function of the H\textsuperscript{-} production surface.

Using IBSimu is better justified for volume production whereas the combination of surface and volume produced H\textsuperscript{-} ions in the extracted beam could be better modelled by combining ONIX and IBSimu -codes. Producing 45 mA with low e/H\textsuperscript{-} -ratio imply that the H\textsuperscript{-} production is surface dominated, which affects the meniscus. The committee supports attempts to identify the role of the two mechanisms (volume and surface) in beam formation through experiments on the test stand. Such experiments have been carried out and documented in Los Alamos National Laboratory with their surface converter ion source clearly exhibiting two components in the extracted beam. Similar experiments at CERN are important for the future high current operation but have lower priority in comparison to qualifying spare sources and operational procedures.

Altogether it is recommended CERN to continue investigating modifications to the existing ion source extraction system to reduce emittance growth using modelling tools and the example of the existing and tested JPARC extraction system to guide the development as several schemes without the einzel lens and shorter LEBT already show considerably lower emittance at higher currents. Opportunities to perform RFQ transmission studies at higher currents using the enhanced source extraction optics schemes should be sought being mindful of beam loss in the RFQ and therefore limiting the RFQ risk.

The committee makes the following further recommendations relevant for the foreseen 45 mA operation presumably starting in 2023.
- Measurement of the actual caesium consumption. The first experiment revealed a factor of 50 discrepancy between the estimated and actual (the latter being lower) caesium flux from the oven into the ion source. This is most likely due to trace amount of impurities affecting the Cs vapour pressure curve. Confirming the result could convince CERN that it is safe to increase the oven temperature with the aim of better controlling the e/H\(^+\)-ratio in long-term operation, which is essential for 45 mA operation.

- The review committee supports designing and testing an LED-based caesium deposition monitoring system capable of detecting small deviations of pure metal work function as presented during the review (or an alternative method). The technique could be used for further assurance of machine protection under elevated caesium flux from the oven.

- We encourage the ion source team to systematically check that the source extraction system operates at the optimum parameters for beam optics e.g. adjusting the extraction voltage to beam current, not only varying the RF power when studying the transmission through the RFQ mask and the actual RFQ.

- It is advisable to revisit the beam current measurement scheme to make sure that the beam current out of the ion source does not include electrons and, vice versa, the electron current recorded from the e-dump does not include H\(^-\) ions lost in the extraction system.

The 2018 Linac4 ion source review found it challenging to assess the likelihood of achieving 45 mA out of the RFQ in 2023. At that time the required beam current was not demonstrated, and it was estimated that 56 mA from the source should be sufficient to reach the goal. The data presented to the 2020 review panel is of better quality but, unfortunately, the situation has not changed, i.e. a direct path to 45 mA was not presented to us. At this time it seems that the current from the ion source should be significantly higher than 56 mA to reach 45 mA even into the RFQ mask. This prompts us to repeat a conclusion from the 2018 review: “This should encourage CERN towards a “staged approach” i.e. increase the current during in 2020 – 2023 beyond 25 mA if it is operationally viable.

The continued development of the source and LEBT presented at the review will likely lead to some increase in operation beam intensity reaching currents on the order of 30-35 mA, but it is unlikely to reach 45 mA alone unless the above discrepancies are understood and solved. Such gradual approach should ease the scheduled transition from 25 mA to 45 mA and enable reacting to possible issues, e.g. flatness of the pulse.” At the same time, it is acknowledged that the observed RFQ damage warrants precautionary measures, i.e. avoiding excessive beam losses in the RFQ, which most likely prohibits gradual increase of the beam current. The situation highlights the importance of a separate RFQ test stand.
The resources do not seem adequate to reach 45 mA by 2023 since there is no allocated time for high current transmission tests with the RFQ and implementing the RFQ test stand as described above would compete for the existing manpower and funding. As a clear path to 45 mA was not presented to the committee, we cannot make further comments on the allocation of resources.

**Executive Summary**

The ABP-HSL (Accelerators and Beam Physics, Hadron Sources & Linacs) team has made significant progress and achieved reliable 25 mA operation from the RFQ into LINAC 4, a central objective of the team.

(i) We believe emphasis should now be directed towards preparing, testing and properly storing 3 (2 spare) near identical sources capable of also meeting this goal. Sustained, stable operation of each source should be demonstrated on the test stand with acceptable e/H⁻-ratios. This should be done prior to accelerator beam production in the fall of 2020. Four-week tests should allow enough time for operational issues to emerge and be resolved with no incursion of real accelerator downtime. This will also allow implementation of written assembly, startup, operation and shut down procedures, which should be strictly followed during these tests and modified if needed. This approach will also demonstrate absolute operational readiness for the upcoming 2020 run.

Regarding the more challenging goal of developing a 45 mA beam out of the RFQ by 2023, we provide many detailed suggestions in the body of this report but believe a high priority should be placed on a few key points:

(i) The ion source test stand will need to become the primary tool for developing the 45 mA source after validating the spare 25 mA sources. The tunnel installation will soon be committed to beam production and the time horizon of a future RFQ test stand is most likely beyond the ~3 year window till 2023. Presently, RFQ acceptance simulation mask transmission data seems to disagree with RFQ transmission measurements possible due to its fixed zero-current geometrical acceptance not accounting for space charge of the beam (see above). We believe that relocating the proven emittance scanner to the theoretical RFQ entrance aperture position on the test stand would give better characterization of the candidate sources and extraction systems and should therefore be considered. These data could then be compared directly to PARMTEQ acceptance simulations of the RFQ
performed at relevant beam currents giving much better estimates of RFQ transmission and the expected 3 MeV beam current.

(ii) It seems that the source/extraction system configurations tested on the RFQ have been shown to have emittance blowup approximately at beam currents where the RFQ transmission decreased. It also seems that much progress at CERN has been made in fine-tuning the ion source extraction system dimensions e.g. by experimenting with the 9 mm extraction aperture, which has shifted this emittance blow up to significantly higher beam currents as measured on the test stand. We therefore recommend continuing to investigate modifications to the existing ion source extraction system to reduce emittance growth at higher beam currents using the test stand configuration described above. Using modelling tools and the example of the proven JPARC extraction system to guide the development is strongly encouraged. In our opinion, trending toward a more JPARC-like configuration will improve emittance and minimize risk by knowing the end point has been proven (see details above).

(iii) Insure RFQ is functioning properly and look for possible testing opportunities. If possible, measure all accessible RFQ RF parameters such as field strength (x-ray) and flatness to ensure the expected field is established. Also look for opportunities to perform RFQ transmission studies at higher currents using the sources developed and proven in (ii) on the test stand described in (i). Limit RFQ risk by being mindful of the beam loss in the RFQ. Finally, a review of the performance of the RFQ is recommended and an assessment on the need to build a modified RFQ is required.