CERN Linac4 Ion Source Review Report

Martin Stockli (ORNL, Chair), James Alessi (BNL), Dan Faircloth (STFC), Olli Tarvainen (JYU)

The purpose of the Linac4 accelerator, under construction at CERN, is to increase the injection energy to the PSB accelerator and, thus the luminosity of the LHC. In order to meet the design specifications of the linac, the ion source has to provide 0.7 ms / 80 mA pulses of H^- ions at 45 keV energy with a repetition rate of 2 Hz. Furthermore, the transverse rms emittance of the extracted beam at nominal current must not exceed 0.25 π·mm·mrad (design value). The availability of the ion source should be ~99.5 %, or the unexpected downtime should not exceed 0.5 %.

The previous review of the Linac4 ion source work package took place at CERN on June 9, 2011. At that time the project was in rather immature state i.e. CERN had no H^- ion source capable of operating at 45 kV source potential. Therefore, a great variety of design options were presented to the committee in 2011. These options included the DESY-type volume production RF ion source, CERN-type volume production RF ion source, CERN-type cesiated RF ion source, high duty factor plasma generator, and BNL-type magnetron. A realistic but challenging project schedule was presented in the first review.

The second review of the Linac4 ion source work package took place at CERN on November 14, 15 2013. The review committee was asked to assess the following three items

1. Review of the Linac4 ion source Work Package; Compare what has been achieved with respect to what was planned and review what is foreseen.
2. Estimate the probability of having a sufficient beam current (40, 60, 80 mA) within the design emittance of 0.25 π·mm·mrad in time for the final commissioning before the connection (February 2016).
3. Is it still necessary to pursue an alternative solution, and is the magnetron source still considered as the most appropriate option? When a decision has to be made and what has to be prepared to make such a source available on-time for the final commissioning of Linac4?

On November 14, the Committee heard 17 presentations from CERN staff, and had a 90 minute tour of the Linac4 building, 3 MeV ion source test stand, and Cs test lab. On November 15, the Committee discussed the presentations, and formulated a set of bullets that were presented to the CERN staff during the close out. The agenda for the review is shown in Appendix 1.

The overall progress of the project has been excellent and all essential deadlines have been met. An H^- beam current of ~20 mA at nominal energy has been reached with the DESY-type volume production source at the ion source test stand and in the Linac4 tunnel. The DESY-type source has served well for the commissioning of the LEBT and the RFQ. The progress of the auxiliary systems e.g. pulsed HV power supplies and RF systems has been equally significant.

The ion source options for reaching the intermediate milestones of 40, 60 and 80 mA have been adequately reduced to two: the CERN-design cesiated RF ion source (later referred as IS02) and the BNL-type magnetron. This is partly due to the failure of the CERN volume production RF ion source to produce any significant H^- current beyond an ignition transient.

The review committee estimated the probability of each source (IS02 and the magnetron) reaching sufficient beam currents of 40, 60 and 80 mA within the emittance design value of 0.25 π·mm·mrad by February 2016. The estimated probabilities are presented in the following table. It is emphasized that the given numbers are based on the current (November 14, 2013) knowledge and take into account all the given constraints. The numbers are subject to change with new experimental evidence.

	IS02	Magnetron
40 mA	90 %	95 %
60 mA	40 %	80 %
80 mA	5-10 %	65 %

The cesiated RF source (IS02) should be considered as the primary option to reach the intermediate goal of 40 mA. Cesiated RF ion sources (SNS, J-PARC) typically produce 2-3 times the current achieved without introducing Cesium. At the same time the ratio of co-extracted electrons to H^- ions is expected to reduce significantly. Since the uncesiated IS02 at CERN produces ~15 mA H^- current it is expected that 40 mA can be likely reached rather quickly. However, this statement must be considered at best as an educated guess until experimental data confirming the estimate is presented. Thus, the committee encourages the Linac4 ion source team to expedite cesiation of the IS02 at the test stand.

An emittance value of 0.5 π·mm·mrad has been measured for the DESY-type RF ion source at beam current below 20 mA. The given number was shown to agree well with simulation studies. Unfortunately the emittance exceeds the design value by a factor of two. Simulation studies indicate that the high emittance could be caused by the extraction ion optics, more precisely the chosen scheme for dumping the co-extracted electrons (e-/H^- ratio is roughly 30 for the uncesiated sources) into a magnetized einzel lens. A speculative simulation in which the co-extracted electrons were artificially removed before entering the electron dump suggests that an emittance of 0.25 π·mm·mrad could be reached with extremely low e/H^- ratio. This underlines the importance of cesiating the IS02. The (presumably) reduced e/H^- ratio should result in lower emittance assuming the afore-mentioned simulation results are close to reality. The reduced electron current would allow optimizing the electron dumping scheme without inducing thermal damage to the extraction electrodes, which could also help lowering the emittance. This highlights the importance of the experiments with cesiated IS02 even further.

The committee suggests continuing the development of the cesiated RF-source towards 60 and 80 mA H^- currents. At the same time the BNL-type magnetron source is perceived as the most likely to succeed option to eventually reach 80 mA. Therefore, the committee recommends that at this point (November 2013) IS02 and the magnetron source should be treated equally in terms of development effort.

At BNL the magnetron source provides up to 100 mA of H^- at 35 keV with 6 Hz repetition rate with a maintenance interval of 3-9 months. In this type of the source mechanical wear is considered as the primary reason for limited lifetime and it can be expected that at 2 Hz the maintenance interval could be even longer. CERN has successfully reproduced the BNL magnetron source and tested its performance up to 40 kV extraction voltage reaching an H^- current of ~140 mA at best (short-term test). The emittance of the extracted beam at this current level is unknown but is most likely exceeds 0.4 $\pi\cdot$mm$\cdot$mrad measured for the BNL source at ~80 mA current. The achieved current is significantly higher than the required 80 mA, which makes it possible to reach the design current without operating the source at its limit. Furthermore it enables reducing the emittance by shrinking the extraction aperture. Significant effort (including simulations and experiments) is required to reach the emittance goal with the magnetron operating at 45 keV final energy. Therefore, it is recommended that CERN either develops an arc power supply or seeks opportunities to borrow one for the magnetron source to expedite its development at the CERN test stand. Operation of the magnetron source requires more Cs than the RF ion source. This could be a potential risk for the RFQ as long-term operation might result in migration of Cesium into the RFQ (although experience at BNL suggests that it will not be a problem). It is therefore suggested to make an experimentally supported assessment of the accumulation rate and its possible consequences.

The modular approach taken in the ion source, extraction system and test stand design makes it possible to continue simultaneous development of both, the IS02 and the magnetron. This is definitely a strength of the project.

To summarize, the presentations to the Committee were well prepared and of high quality. The Committee was very impressed by the progress made since the last review, and concluded that the project is on a proper path to meeting Linac4 requirements by continuing to develop in parallel both the CERN cesiated volume H^- source and the magnetron surface plasma H^- source. The many parallel activities, both related to the necessary ion source R&D and providing beams for project component testing, seem to be very well managed. The Committee was also very impressed by what was seen during the facility tour. The front end installation on Linac4 was of top quality, and the ion source test stand and cesium test stand were important for the ongoing development work which is necessary. The Ion Source Group should also be commended for the use of students and fellows on the project, and for the large number of publications that have already come out of this work.

Update (December 2013): The result of the first cesiation attempt of the IS02 was brought to the attention of the review committee members in mid-December, 2013. The CERN ion source team had successfully demonstrated an H^- beam current of 50 mA accompanied by a very significant *reduction of the electron to H^- ratio (from 30-40 in volume production mode to 4 in operation with Cesium). At this time the corresponding emittance is unknown. Therefore, it is premature to change the assessment presented above.*

A few additional comments on the various subsystem presentations follow:

IS-01 Ion Source

IS-01 only produced a 3 mA 40 µs spike for H^- with 3 A of co-extracted electrons. It was unfortunate that after a very short test IS-01 was abandoned due to lack of time, but this was unavoidable and the correct decision.

The Cs-feed line is far from the active conversion surface. A thermocouple should be installed to monitor the Mo-surface temperature.

Design, Engineering and production

The nice modular design of source components makes it easier to make improvements and to switch between sources used.

Great progress seems to have been made in antenna development.

The redesigned extractor and electron dump now allow routine operation at 45 kV.

Many problems have been overcome in the high voltage insulator design. Out gassing and inclusion problems with the epoxy glass fibre reinforced insulator have been successfully dealt with by filling the region with SF6. Electrostatic finite element modelling could be used to aid the high voltage design and to help eliminate triple junctions.

Power converters

It is a very nice achievement that there are now 3 operational full systems (power electronics and transformers) for the H^- (H^+) pulsed electrodes - extraction, puller, and e-dump. The systems produce 700 µs flat-top, using <1 kV low voltage to pulse transformer, in a stacked transformer configuration. They have spark detection and voltage inhibit. This seems to be a very good, robust system.

The project is considering whether the magnetron arc discharge power converter could be based on this existing design. A decision is needed to materialize this opportunity. They should explore also options used at other labs, which could be simpler and cheaper.

H_2 injection system

The hydrogen gas systems are based on similar setups used for the LHC experiments (which have >99.9% availability). There are four systems - one each for source and LEBT on both the operating system and the test stand. The systems are well thought out with respect to both safety and different operational modes. They have been successfully used now for > 1 year. The LEBT system can be operated with different gases, and it is likely that a gas other than H_2 will be best for LEBT.

Pumping systems, Residual gas analyzer

Very nice simulations of the gas pulsing have been done, with benchmarking against actual results.

Peak pressure measured in the LEBT is higher than the design value, which will result in a higher gas load to the RFQ and lower operational time between reactivations of the NEG pumps (an availability issue, since they desire 1 year of operation between regenerations).

It is not clear why operation of the ion source at 2 Hz exceeds their maximum desired pressure in the RFQ.

Beam diagnostics

There is a good suite of diagnostic devices for the ion source test stand. Generally, these are the same as used on Linac4 where possible.

RF-Design, Controls

Two ion source rf systems have been installed (Linac4 tunnel and Test Stand). Spares of all critical parts exist. While there have been a couple of incidents causing downtime (so far), the system is very robust. The RF-system is probably the best-tested subsystem.

Beam optics simulation, measurements

The redesigned extraction system with electron dumping seems to be working very well, now routinely operating at 45 kV. The simulations of beam extraction of ions with dumping of electrons have been essential to the proper design of this beam extraction system. The agreement between simulations and measurements is very good, and the larger than desired measured beam emittance can be explained by the large co-extracted electron current in the uncesiated source. Remarkable difference in emittance (> 0.5 → 0.2-0.25) in the simulations if electrons are artificially removed before the e-dump! Speaks for the surface source (cesiation). e/H^- ratio measurement and emittance measurement of the IS02 after cesiation defines the path forward.

These very successful simulations should also be applied to the magnetron source extraction system, which would likely gain from a similar optimization.

Timing, Control system, Operation, GUI applications, database

There don't seem to be any issues with the ion source control system, which is based on the existing LHC and injectors control systems. All hardware and software seems well in hand for operation of the Linac4 and Test Stand sources. One FTE is needed to implement magnetron source controls.

BNL-type magnetron source

The project has done a very nice job of manufacturing a working version of the magnetron source. The production of a full set of CAD drawings from marked up BNL drawings was completed at CERN, and manufactured source components were then successfully tested at BNL. The tests at BNL give reassurance that the CERN copy of the source will perform in a similar manner. The CERN produced source operated at 6.6 Hz and 2 Hz at BNL, giving 145 mA peak H^- current at 39.5 kV (the BNL ps voltage limit).

CERN now needs to set up a test stand to develop and test the magnetron to ensure that it can deliver the beam emittance requirements at 80 mA. Alternatively, they could check with ESS-Bilbao to see if they could operate the magnetron source on their test stand, or loan an arc pulser to CERN for quicker testing.

The IBSimu simulations at CERN of ion and electron extraction, plus calculations related to erosion of source parts seen at BNL, have led to a good understanding by the CERN project of magnetron operation and issues.

Although not an issue at all at BNL, CERN needs to determine whether in their case cesium from the source could migrate into the RFQ and cause problems. Measurements at CERN at some downstream location while operating the magnetron for long periods on the test stand could help in this regard.

Plasma simulation, OES, OEP monitoring

This is very interesting work, trying to describe the evolution of the plasma from ignition to steady state. Ever increasing computing power will yield deeper insights into source operation. This type simulation could eventually assist in source optimization, but H^- production mechanisms are not yet included in the simulations. It is of value to continue this work, as long as it does not strain resources needed for other parts of the project.

RF field simulation

This is another piece of nice fundamental work that helps in the understanding the physics of the source rf/antenna/plasma system.

LEBT, beam neutralization, Hydrogen injection for space charge compensation

Two LEBTs are installed and operational - one on Linac4, and one on the ion source test stand. The test stand LEBT is very valuable for source testing, plus many components also serve as spares for the Linac4 LEBT. Everything here seems to be working very well!

Safety aspects HT, Gas, Cs, Electrical, Fire

Primary hazards for the ion sources are electrical, non-ionizing radiation, chemicals, pressurized systems, and flammable gas. The team seems to be very safety conscious, with procedures being developed for the more hazardous tasks. All work is handled within CERN safety rules and regulations. The H_2 gas systems and Cs handling both seem well thought out. (One should be sure to check for possible x-rays from operation of the sources at 45 kV).

Engineering

Many of the source components have been subject to careful engineering analysis, which was nice to see. The main insulator is a critical piece in terms of the project timeline. Emittance improvement predicted by inserting the source further inside (eliminate the second einzel lens?) requires a new main insulator design, which is expected to take 1-1.5 years for engineering and production.

Visit to Linac4 building, 3 MeV Ion Source test stand and Cs-laboratory;

The committee was very impressed by what it saw during the 90 minute tour of the Linac4 building, 3-MeV ion source test stand, and Cs test lab. It was great to see the careful, professional source installation on Linac4. The ion source test stand will clearly be a valuable resource for many years, providing a place to test improvements, etc. Finally, the Cs test stand has been very effective for gaining Cs handling experience, and very robust procedures for Cs oven filling and cleaning have been developed. The Cs delivery system is very well designed and characterised. Several questions which came up while looking at the Cs system were the possible heating of Cs collar rather than just cooling, and possibility for Cs refill during operation.

Summary (bullets presented at closeout)

Review of the linac4 ion source Work Package; Compare what has been achieved with respect to what was planned and review what is foreseen.

- Essential deadlines have been met
- The options have been adequately cut down to IS02 and the magnetron
- Achievements (not in specific order):
  - Implementation of the HV pulsers
  - Redesigning the extraction and running it at 45 kV, dumping the electrons in controlled manner
  - Modular approach
  - Source installation in the tunnel
  - Excellent safety practices
  - Operational LEBT (and RFQ)
  - Successfull testing of the magnetron
  - Plasma simulations
  - Student and fellow involvement.
- Concerns:
  - Cesiation must be pursued more aggressively – it is a critical step!
  - Emittance – the real test is transmission through the RFQ

Estimate the probability of having a sufficient beam current (40, 60, 80 mA) within the right emittance (0.25 mmmrad) in time for the final commissioning before the connection (February 2016).

Probability estimate taking into account the given current and emittance

	IS02	**Magnetron**
40 mA	90 %	95 %
60 mA	40 %	80 %
80 mA	5-10 %	65 %

Cesiated IS02 should be considered as the best and quickest option for 40 mA
It is advisable to expedite the cesiation and emittance measurements of IS02

Is it still necessary to pursue an alternative solution, and is the magnetron source still considered as the most appropriate option? When a decision has to be made and what has to be prepared to make such a source available on-time for the final commissioning of Linac4?

- Cesiated IS02 should be considered as the best and quickest option for 40 mA
- Development of the cesiated RF-sources needs to be continued towards 60 and 80 mA / 0.25 π·mm·mrad goals.
- The magnetron source should be pursued as the most likely to succeed option to eventually reach 80 mA.
- Work is required to reduce the emittance of the magnetron source to 0.25 π·mm·mrad.
- At this point IS02 and the magnetron source should be treated equally in terms of development effort.

- Required for the magnetron source
  - Arc pulser - borrowing as an interim solution?
  - Experiments on the test bench.
  - Experimental development of the extraction system supported by simulations.
  - Experimentally supported assessment of the possible entry of Cs into the RFQ.

APPENDIX 1 - AGENDA

Thursday, 14 November 2013

09:00 - 09:10 Welcoming address and mandate ; Roland Garoby (CERN)

09:10 - 09:25 Status of Linac4 ; Maurizio Vretenar (CERN)

09:25 - 10:05 Overview of Linac4 H^- source: Status, outlook ; Jacques Lettry (CERN)

10:05 - 10:20 Design, Engineering and production ; Didier Steyaert (CERN), Serge Mathot (CERN), Pierre Moyret (CERN)

10:20 - 10:35 Coffee break

10:35 - 10:50 Power converters (; Davide Aguglia (CERN), David Nisbet (CERN)

10:50 - 11:05 H2 injection system ; Roberto Guida (CERN), Jacques Rochez (CERN)

11:05 - 11:20 Pumping systems, Residual gas analyzer ; Chiara Pasquino (CERN), Paolo Chiggiato (CERN), Jan Hansen (CERN)

11:20 - 11:35 Beam diagnostics ; Uli Raich (CERN)

11:35 - 11:55 RF-Design, Controls ; Mauro Paoluzzi (CERN), Andy Butterworth (CERN)

11:55 - 12:15 Beam optics simulation, measurements ; Oystein Midttun (University of Oslo (NO))

12:15 - 13:30 Lunch

13:30 - 15:00 Visit to Linac4 building, 3 MeV Ion Source test stand and Cs-laboratory; Conveners: Maurizio Vretenar (CERN), Jacques Lettry (CERN), Richard Scrivens (CERN)

15:00 - 15:20 Timing, Control system, Operation, GUI applications, database; Jose-Luis Sanchez Alvarez (CERN), Ioan Kozsar (CERN), Jaime Gil Flores (CERN), Michael O'Neil (CERN), Patrik Andersson (CERN)

15:20 - 15:50 BNL-type magnetron source ; Jacques Lettry (CERN)

15:50 - 16:10 Plasma simulation, OES, OEP monitoring ; Stefano Mattei (CERN)

16:10 - 16:25 Coffee break

16:25 - 16:40 RF fields simulation ; Alexej Grudiev (CERN)

16:40 - 17:00 LEBT, beam neutralization, Hydrogen injection for space charge compensation ; Richard Scrivens (CERN)

17:00 - 17:15 Safety aspects HT, Gas, Cs, Electrical, Fire ; Anne Funken (CERN)

17:15 - 17:30 Engineering ; Marco Garlasche (CERN), Alessandro Dallocchio (CERN)

17:30 - 17:50 Discussion, wrap-up, additional information

19:30 - 22:00 Dinner with the committee members

Friday, 15 November 2013

09:00 - 11:30 Preparation of a bullet point conclusion

11:30 - 12:00 Presentation of the preliminary report

12:00 - 13:00 Lunch