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SOURCE AND LINAC3 STUDIES

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Abstract

In the framework of the LHC Ion Injector Upgrade programme (LIU), several activities have been carried out in 2016 to improve the ion source and Linac3 performance, with the goal to increase the beam current routinely delivered to LEIR. The extraction region of the GTS-LHC ion source was upgraded with enlarged vacuum chamber apertures and the addition of an einzel lens, yielding higher transmission through the rest of the machine. Also, a series of experiments have been performed to study the effects of double frequency mixing on the afterglow performance of the source after installation of a Travelling Wave Tube Amplifier (TWTA) as secondary microwave source at variable frequency. Measurements have been carried out at a dedicated oven test stand for better understanding of the ion source performance. Finally, several MD sessions were dedicated to the study and characterization of the stripping foils, after evidence of degradation in time was discovered in the 2015 run.

SOURCE EXTRACTION UPGRADE

In the framework of the LHC Injector Upgrade project, which aims to improve the performance of the CERN accelerator chain in preparation for future high luminosity operation of the LHC, several studies for beam intensity improvement at Linac3 have been launched, with the goal of increasing the extracted intensity by 20% by LS2.

Simulations of beam formation and extraction from the 14.5GHz Electron Cyclotron Resonance (ECR) GTS-LHC ion source and subsequent beam tracking in the low-energy part of the Linac revealed significant beam losses from collimation on the chamber walls due to the very high beam divergence at source extraction. In order to address this issue, a re-design of the source extraction system was launched and implemented during YETS 2015-2016. This consisted in 1) the removal of the beampipe aperture limitation, with increase of the chamber diameter from 65 to 100mm; and 2) the installation of an electrostatic einzel lens as additional focusing element between the existing source extraction electrodes and the first beamline solenoid (see Fig.1). A 20% beam transmission increase through the LEBT was expected from simulations of upgrade 1), which was nicely confirmed in operation, with an increase in the average lead beam current measured at the RFQ input from 170mA during the 2015 run to 210mA in 2016 (Fig.2).

A thorough campaign of beam measurements was carried out to characterize beam parameters. Transverse emittances were measured indirectly via a quadrupole scan technique and tomographic reconstruction of the beam distribution from profile measurements at the SEMgrid in the LEBT section.

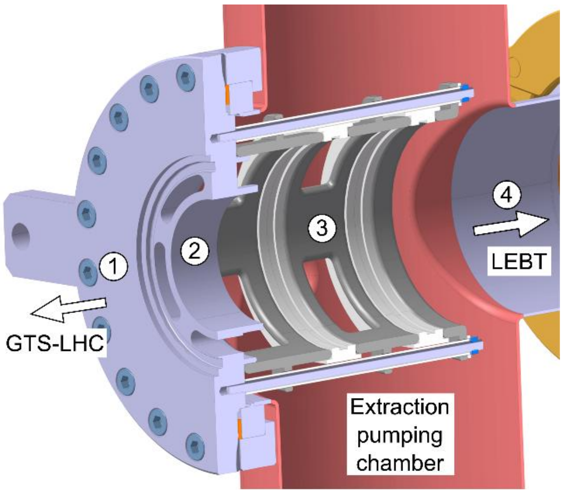

Figure 1 Mechanical design of the source extraction upgrade.

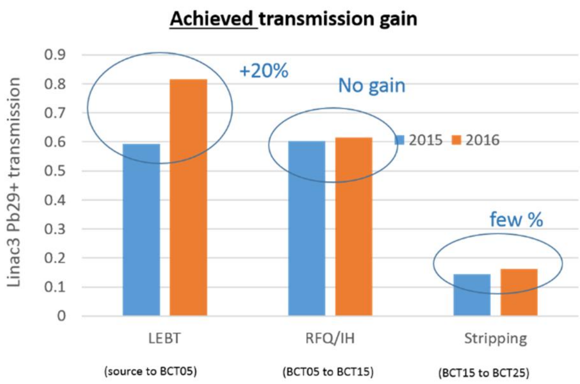

Figure 2 Transmission gain along Linac3 from 2015 to 2016 operation.

Beam emittances at the RFQ input were found to vary between 0.18 and 0.25 mm mrad (RMS normalised values) in both horizontal and vertical planes. This exceeds the design transverse acceptance of the RFQ (200 mm mrad), making this the next transport bottleneck in Linac3 (with 60% average transmission in operation at nominal voltage).

LINAC3 ACTIVITIES IN 2016

A systematic campaign of beam measurements was carried out in 2016, for more precise characterization of beam parameters at Linac3 and validation of the simulation models assumed to study the machine. Several methods to improve beam performance and intensity delivered to LEIR were investigated throughout the year, as listed here in the following.

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Einzel lens studies

The einzel lens has been designed to be operated in accelerating or decelerating mode with absolute voltages up to 20kV. Simulation studies of beam extraction in presence of the einzel lens predicted an additional gain in the beam intensity transported downstream, on top of the one achieved by increasing the vacuum chamber aperture. The main benefit of the einzel lens installation was however expected to come from enhanced control of the beam properties via the separation between the ion source tuning and beam transport optimisation, providing higher flexibility to the ion source operation and potential to improve performance. Linac3 has effectively been run in 2016 with different source settings than in the past, leading to better beam matching to the rest of the accelerator. No remarkable gain in transmission through the spectrometer was however observed when applying non-zero (positive or negative) voltages to the einzel lens, as was instead expected from simulation studies (see Fig.3).

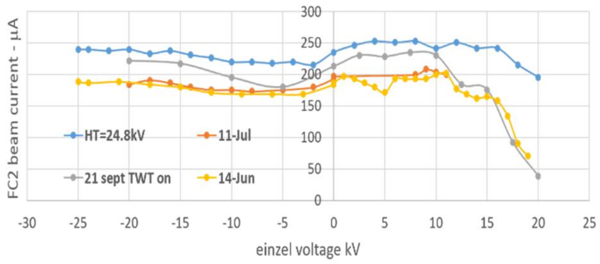


Figure 3 Measured beam transmission after the Linac3 LEBT spectrometer while scanning the voltage applied to the einzel lens. The orange and yellow curves correspond to standard settings, the blue curve has been taken for higher extraction voltage from the source, and the grey curve is for operation with the TWTA switched on.

Double frequency operation

Using multiple discrete frequencies simultaneously for ECR plasma heating is a well-established method to improve ion source performance with high charge state production. Experiments have however mainly been conducted with ECR ion sources operated in CW mode.
Investigations have been carried out this year at the GTS-LHC source to study the effects on afterglow operation.

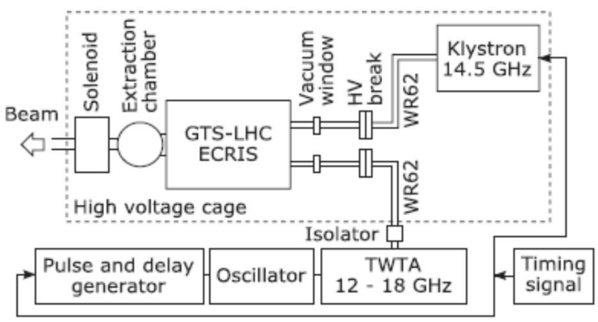


Figure 4 Double-frequency measurement setup at Linac3.

The measurements setup is shown in Fig.4. The primary 14.5GHz microwave radiation is provided by a klystron amplifier at 10Hz repetition rate and 50% duty factor. The spare waveguide is connected to a Travelling Wave Tube Amplifier (TWTA) to deliver microwaves at variable secondary frequency (in a 12-18 GHz range).The maximum power delivered from the amplifier was ~300W. The input signal was generated by a variable frequency oscillator and the pulse generator was triggered by the klystron timing signal, thus allowing pulsed operation of the TWTA. A first assembly was installed in April 2016 with borrowed units; these were later on purchased and made the object of a second installation in September 2016.
A shift to higher charge states was indeed observed when the secondary frequency was chosen to be lower than the primary one, whereas the effect was much weaker in the opposite case. It was also verified that the shift was not just due to an increased total microwave power. The best results for Pb^{29+} were obtained with 14.2GHz pulsed secondary frequency, with beam current improvements of 10% after the RFQ and 5% downstream of the IH linac after rematching. No significant changes were observed in measured beam parameters (mainly transverse emittance and RFQ transmission) with the TWTA ON or OFF.
Some negative effects were however observed in the overall beam stability out of the source, justifying an interruption of the double frequency operation when beam was finally delivered to the LHC for the physics run.

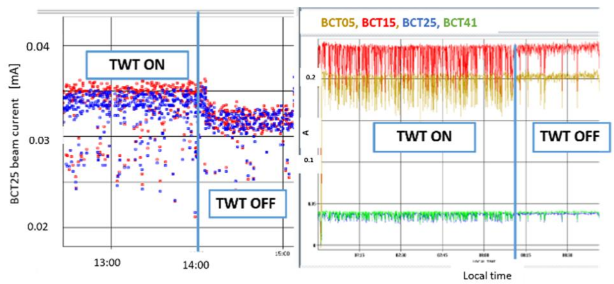
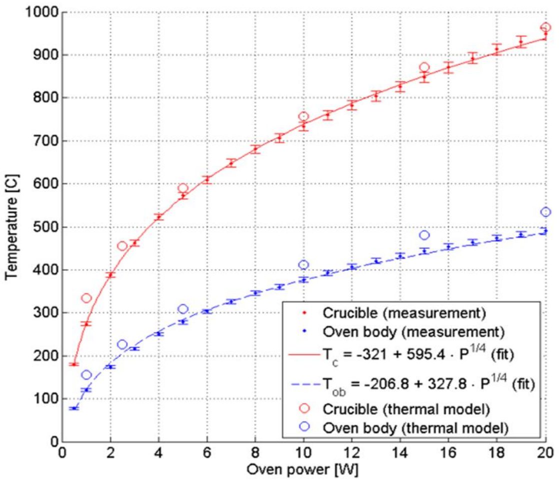


Figure 5 TWTA effect on transmission downstream of the IH, as measured on the BCT25 current transformer (left), and on beam stability (right).

Oven test stand studies

The Linac3 Lead ion beams are produced in the GTS-LHC source using resistively heated ovens, consisting of an aluminium oxide crucible, tantalum heating filament and oven body and stainless steel cane allowing insertion through the ion source. In order to study oven performance and get better understanding of failure mechanisms, a dedicated offline test stand has been constructed in the South Hall of bldg. 152 with the goal of measuring oven temperatures and Lead evaporation rates in varied input conditions. Fig.6 shows the measured temperature characterization of the oven. For operational values of the input power between 6W and 20W, the crucible temperature varies between 600 ºC and 950 ºC, following a $T{\sim}P^{1/4}$ relationship characteristic of radiative losses. The response to input power changes is slow, as observed in operation.



$$T_{crucible} = 54.6 + 1.8\, T_{oven\ body}$$

Figure 6 Measured crucible and oven body temperatures as function of the oven input power, compared to model predictions.

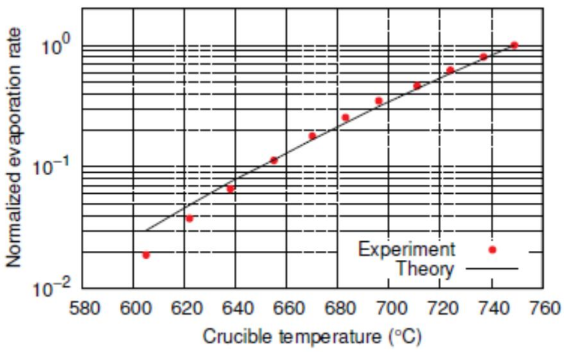


Figure 7 Evaporation rates as function of the crucible temperatures.

Measurements of the lead evaporation rate (Fig.7) show a steady response of the output as a function of the crucible temperature, as predicted by theory. At constant power, on the other hand, the oven output is observed to decrease steadily over time as seen in operation, where a regular power adjustment is needed to keep the necessary lead evaporation rate for beam production.

A numerical thermal model of the oven has also been developed with the ANSYS code to complement the measurements and provide insight on the temperature distribution inside the oven. Simulation results have been compared to temperature measurements at selected locations and found to be in good agreement with them. Fig.9 shows ANSYS results for the case of 10W and 15W heating power. They show good temperature uniformity in the lead

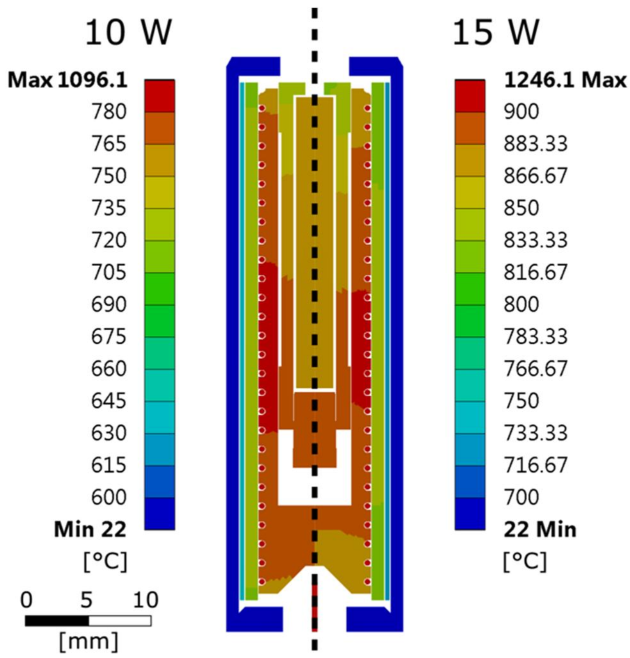


Figure 8 ANSYS simulations of the temperature distribution inside the oven.

sample, with a significantly colder tip of the oven, which could explain the oven blockages experienced in operation.

Stripping foil studies

Several Linac3 MD sessions were dedicated to the characterization of stripping foils, after 2015 measurements showed measurable signs of degradation after few weeks of usage. The stripped beam average energy and energy spread are calculated from beam profile measurements in the ITFS spectrometer line, with the ramping cavity at zero-crossing phase. Measurements taken at the end of the 2015 run (see Fig.9) show clearly a shift to higher values of the average beam energy and considerable energy spread broadening of the beam passing through the three foils used during the year at different periods with respect to the unused foils.

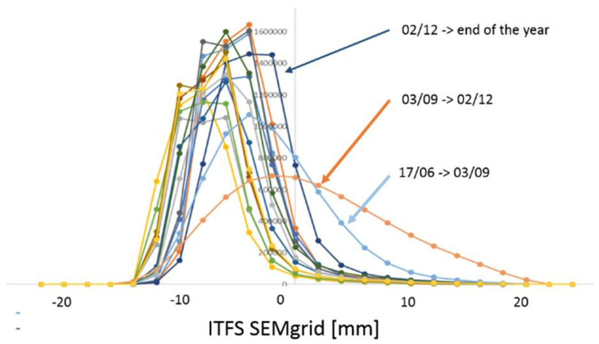


Figure 9 2015 beam profiles measurements in ITFS line.

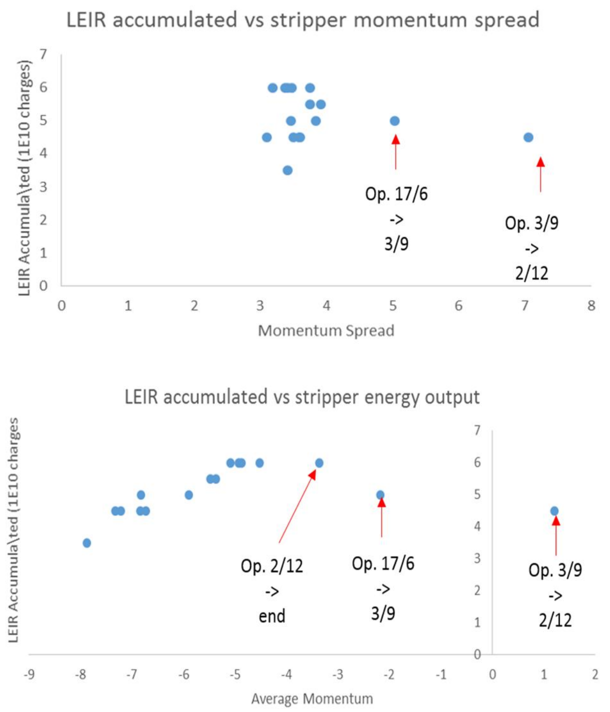


Figure 10 Correlation of LEIR accumulated intensity with stripper energy and momentum spread output.

These measurements were correlated with accumulated intensity in LEIR without changing the linac energy nor transfer beam-line settings (see Fig.10). The accumulation efficiency is found to be nearly independent of the energy spread, with only a small reduction for foils in use for a longer time. The average energy instead was found to be of major importance for the injection efficiency, with a plateau width of <10 keV/u.

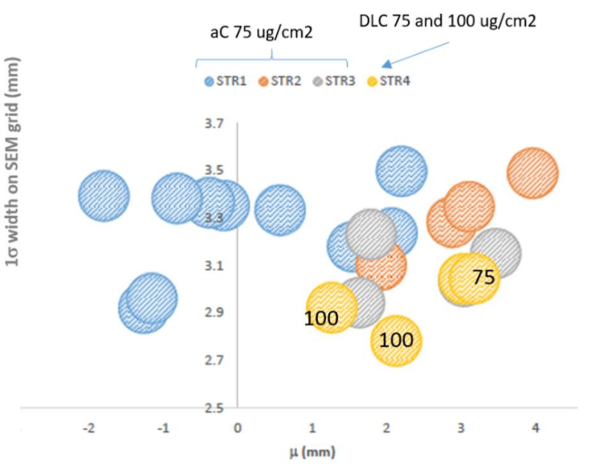


Figure 11 Measured variation in average energy and energy spread of the stripped beam (end of May 2016).

Fig.11 summarises some foil characterization measurements taken in 2016 after several weeks of beam operation. Four Diamond-Like-Carbon (DLC) foils were installed at the time, with a thickness of 75 and 100 μg/cm^2 (in yellow). All the other twelve foils are of the amorphous-Carbon (aC) type, with a thickness of 75 μg/cm^2 (and a tolerance of <5 μg/cm^2). Different colours are used for foils on different arms. Also, two to three measurements at different positions within the foil were carried out for the STR1 foils, which explains the ten blue points in the diagram.
The mean energy out of the aC foils varies within a range of 27 keV/u between the foils (assuming 4.5 keV/u/mm conversion factor of the spectrometer line), which is significant compared to the calculated energy loss of 42 keV/u through a 75 μg/cm^2 foil. Variation within a single foil when positioning the beam at different spots is relatively modest, less than 5 keV/u, but differences from foil to foil can be quite significant, suggesting that thickness could vary significantly between different foils. Charge State Distribution (CSD) scans measured for all different foils hint to the fact that DLC foils might be too thin (even if the calculated equilibrium thickness is ~75 μg/cm^2). There is also indication that DLC foils are less robust and performant than aC foils.

CONCLUSIONS

Thanks to the upgrade of the GTS-LHC source extraction region during YETS2015-6, higher beam currents are now routinely delivered to LEIR satisfying the Linac3 output intensity goal set in the LIU project. A dedicated campaign of measurements has been pursued in 2016 to achieve better understanding of the beam dynamics in Linac3 and for validation of the machine model in the simulation codes used. The effects of additional einzel lens focusing and of double frequency mixing in the source plasma have started to be investigated with the goal of achieving either an even higher intensity or just a more robust and reliable beam operation. This latter point has now become the main objective of LIU-related studies at Linac3, which will develop along three main directions:

i. Understanding of the source performance (oven test stand activities, double-frequency heating, einzel lens and development of an application for automatic regulation of the source)
ii. Machine model validation (space charge compensation studies in the LEBT, studies for a higher extraction voltage)
iii. Understanding of the stripper foils performance (characterization of degradation, monitoring of beam trajectory/energy evolution, foil swapping procedures etc.)

The 2017 scheduled operation of Linac3 is with Xenon ions; though adapted to the different particle species, the Linac3 study campaign will continue with regular weekly MD sessions, profiting from the better beam stability and regularity.