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HIGH INTENSITY PROTON BEAMS AT GSI (HEAVY ION) UNILAC

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Abstract

A significant part of the experimental program at FAIR is dedicated to pbar physics requiring a high number of cooled pbars per hour. The primary proton beam has to be provided by a 70 MeV proton linac followed by two synchrotrons. The new FAIR proton linac will deliver a pulsed high intensity proton beam of up to 35 mA of 36 µs duration at a repetition rate of 4 Hz. The GSI heavy ion linac (UNILAC) is able to deliver intense heavy ion beams for injection into SIS18, but it is not suitable for FAIR relevant proton beam operation. In an advanced machine investigation program it has been shown, that the UNILAC provides for sufficient high intensities of CH_3-beam, cracked (and stripped) in a supersonic nitrogen gas jet into protons and carbon ions. This new operational approach results in up to 3 mA of proton intensity at a maximum beam energy of 20 MeV, 100 µs pulse duration and a rep. rate of 4 Hz. For some time now, UNILAC proton beam operation with higher intensities has been offered as standard for users. Recent linac beam measurements will be presented, showing that the UNILAC is able to bridge the time until the FAIR-proton linac delivers high-intensity proton beams.

INTRODUCTION

Besides two ion source terminals and a low energy beam transport system (LEBT) the High Current Injector (HSI) [1] of the UNILAC (Fig. 1) comprises a 36 MHz IH-RFQ (2.2 keV/u up to 120 keV/u) and an IH-DTL with two separate tanks, accelerating the beam up to the final HSI-energy of 1.4 MeV/u. After stripping and charge state separation the Alvarez DTL provides for beam acceleration up to β = 0.155. In the transfer line (TK) to the synchrotron SIS18 a foil stripper and another charge state separator system can be used. In order to provide the highest heavy ion beam currents (15 emA, U^{28+}), as required for FAIR, the HSI must deliver up to $2.8 \cdot 10^{12}$ U^{4+} ions per pulse [2].

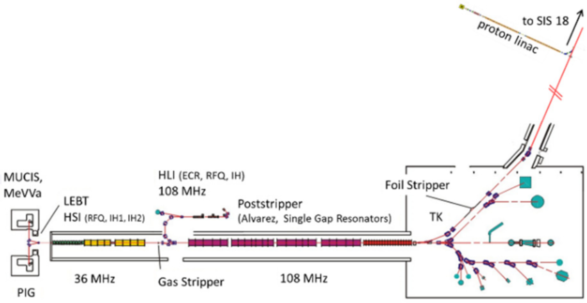

Figure 1: Schematic overview of the GSI UNILAC, experimental area and new FAIR proton linac.

Highly charged heavy ion beams as well as protons, both with high average intensities (but low pulse intensities), from an ECR ion source of CAPRICE-type are accelerated in the High Charge State Injector (HLI) to 1.4 MeV/u. The HLI as well as the HSI serve in a time sharing mode for the Alvarez DTL. The FAIR proton linac [3] has to provide the high intensity primary proton beam for the production of antiprotons. It will deliver a 70 MeV beam to the SIS18 with a repetition rate of 4 Hz. The proton linac will be located north of the existing UNILAC complex. The main beam parameters are listed in Table 1.

Table 1: Main Parameters of the FAIR Proton Linac

Final energy	70 MeV
Pulse current	up to 70 mA
Protons per pulse	$7 \cdot 10^{12}$
Repetition rate	4 Hz
Transversal beam emittance	4.2 µm (tot. norm.)
rf-frequency	325.224 MHz

PROTON BEAMS AT HEAVY ION LINACS

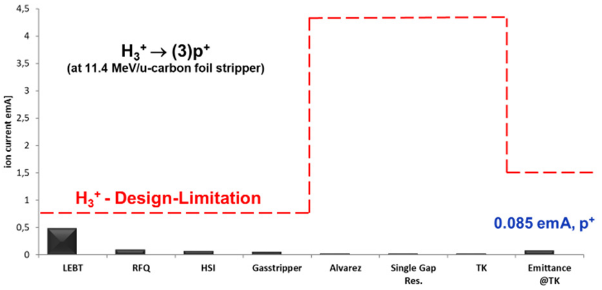

Figure 2: Standard proton beam operation at GSI-UNILAC.

The GSI heavy ion linac (UNILAC) is able to deliver intense heavy ion beam for injection into SIS18, but it is not suitable for FAIR relevant proton beam operation. A strong limitation for light ion beam operation is the low extraction voltage, applied at the ion source due to the fixed specific ion energy of 2.2 keV/u at the RFQ entrance. This limits strongly the extracted beam current from the ion source. Due to the huge emittance in the LEBT only ≤20% of the H_3^+-beam could be accepted by the HSI-RFQ, minor additional particle losses in the matching section to the HSI-IH-DTL limits the overall HSI-transmission to 17%.

Anyway, the significantly higher design limit at Alvarez DTL for H_3^+-beam and for high energy proton beam behind carbon foil stripping can by far not be utilized in standard operation (see Fig. 2).

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UNILAC MACHINE INVESTIGATIONS

Recently an advanced investigation program at the existing UNILAC was successfully pushed to deliver high intensity proton beams up to the UNILAC (Alvarez DTL) design limit for a dedicated experimental program at SIS18. In this frame CH_3^+-beam operation with a MUlti Cusp Ion Source (MUCIS) [4] was established (see Fig. 3). The maximum achieved beam current (for methane operation) was 11 mA for the not analyzed beam and 4 mA for the CH_3^+ ion beam. The ion source operation has been performed with a repetition frequency of 2 Hz and a pulse length of 1 ms. The ethane gas tests have been carried out with the same ion source and under the same conditions, but the mass spectrum is more complex than for methane operation (see Fig. 3). The production maximum was obtained for $C_2H_4^+$, while a maximum beam current of 2.0 emA in front of the RFQ was achieved. However, assuming the same transmission through the HSI, CH_3^+ beam operation results in a higher proton yield. Due to the higher applied extraction voltage and the enhanced HSI design limit for CH_3^+-beam operation, the improved beam transmission compared to a pure proton beam is evident. Furthermore a triple particle output (for protons) from each CH_3^+ molecule behind the stripping section [5] can be anticipated.

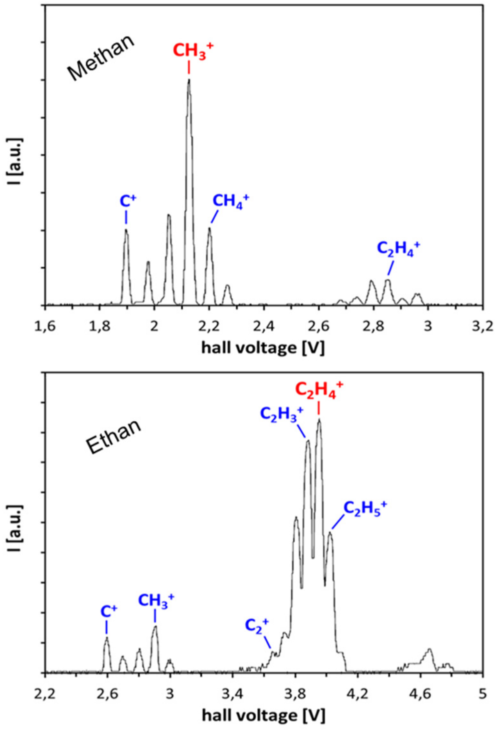

Figure 3: Ion source development in order to provide for high intensity hydro carbon compound beams. [6]

Acceleration of protons at UNILAC implicates special challenges for the settings of the high power rf sections. Designed and normally operated at rf levels between some 100 kW up to 2 MW, in particular the low level part (amplitude and phase control) has to be adjusted to handle very low signal levels. The cavity voltage for the Alvarez tank 3, shown in Fig. 4 corresponds to an output power of approximately 21 kW. The adjustment of the rise time setting has to ensure a constant gap voltage (flat top) at the time when the beam pulse is passing the cavity. The overall loop gain had to be increased up to a non-risky level. The reaction on the proton beam is shown in Fig. 4 as well. Due to the lowered cavity impedance while the beam is present the control loop increases rf power in the range of 4 kW in addition to the 21 kW for the cavity losses.

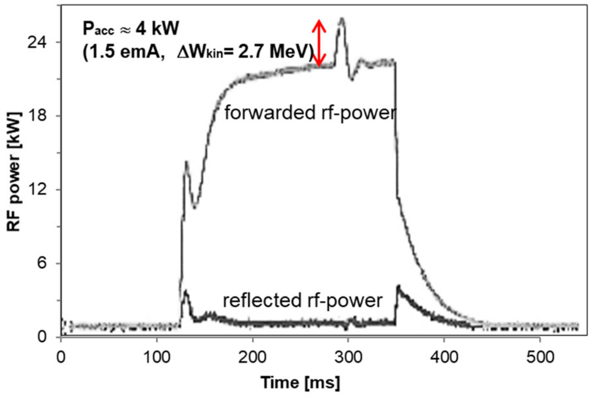

Figure 4: RF-amplifier optimizations. [6]

HIGH INTENSITY MEASUREMENTS

A dedicated machine investigation program was carried out to push the proton beam intensity at GSI-UNILAC. The highest proton intensity of 4 mA (at 1.4 MeVu) was achieved in a test experiment with $C_2H_4^+$-beam from the HSI. Finally in 2016, a thirty times higher proton current was available at standard beam energy of 11.4 MeV/u. Strong efforts were launched to push the high current proton beam transmission through the entire poststripper and transfer line to a value of up to 80% (for 2.0 mA).

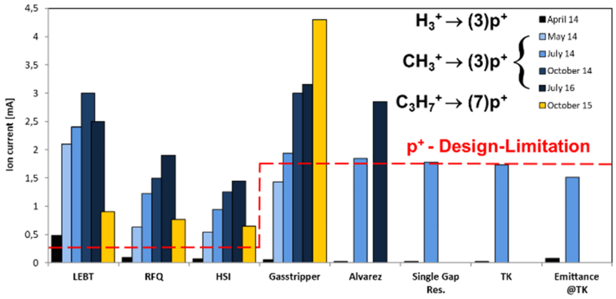

Figure 5: Proton beam intensity at UNILAC. [6]

The high current transverse beam emittance was measured with high resolution in all sections of the UNILAC and the transfer line (Fig. 6). The transverse emittance growth inside the entire Alvarez section could be minimized to 17% only. Even though a transmission loss was observed in the transfer line to the SIS18, the beam brilliance was kept constant during beam transport. The bottleneck of the beam transport line is a 22.5 degree bending

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magnet with a limited aperture implicating transmission loss of approx. 10% for high current proton beam operation.

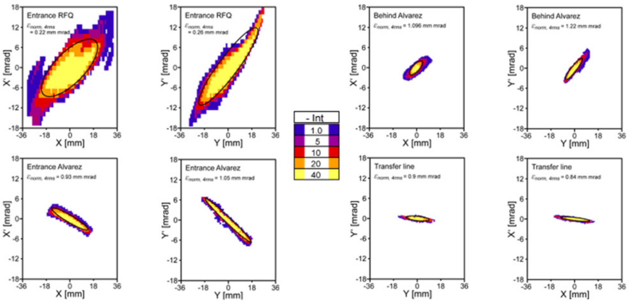

Figure 6: Proton beam emittance measurements corresponding to Fig. 5 (May 2014). [6]

HIGH PERFORMANCE PROTON BEAM OPERATION

For the applied (pulsed) H_2-gas target at 1.4 MeV/u stripper section the CH_3^+-molecules are stripped and cracked in one carbon ion and three protons. In the charge separating system comprising three dipole magnets the high intensity proton beam is separated from the carbon beam. The measured charge spectrum (Fig. 7) shows a proton fraction, which is (above a certain threshold) independent on the density of the supersonic nitrogen gas jet target. The average charge of the carbon spectrum depends on the target density. A maximum at Z = 4 for lower gas pressure and at Z = 6 for highest gas pressure was observed. For advanced proton beam operation the lowest target density, providing for high beam intensities as well as for minimum beam straggling (minimum emittance growth), has been adjusted. The entire spectrum is influenced by the different secondary electron multiplying factors of proton and carbon beams; especially the relatively low measured proton beam current signal (compared to the carbon beam current signal) was not investigated in detail.

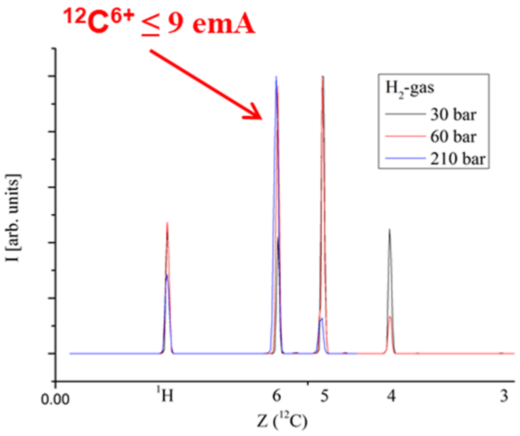

Figure 7: Stripper spectrum optimized for C^{6+}. [6]

Proton acceleration in the Alvarez post stripper requires very low rf voltages, as long as the regular synchronous phase of -30° (resp. -25° for Alvarez tank 3 and 4) is applied. In order to operate at these low voltages, the rf transmitters have to be tuned carefully providing for stable and reliable proton beam operation. This strong effort and long lasting tuning procedure can be avoided, when larger negative phases for the reference particle are chosen: For the same peak voltage the instantaneous voltage for the reference particle is then lower ($U(\varphi)=U_{peak}*\cos\varphi$). Accordingly, for the same reference particle voltage higher rf peak voltages can be applied. During 2020 machine experiment campaign with high current (2 emA) proton beams it turned out that a phase value of -57° is the best compromise for sufficient beam properties at managable rf control-voltages for all Alvarez-tanks. As shown in Fig. 8 the beam emittance is increased by almost a factor of, 2 while beam transmission is not significantly changed.

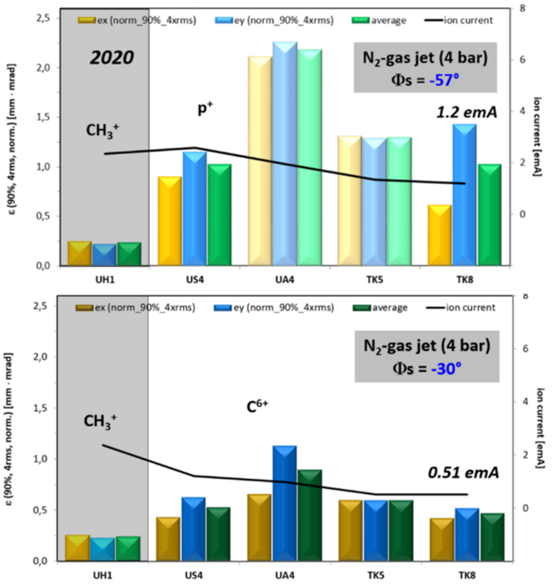

Figure 8: Simultaneous poststripper operation with high intensity carbon and proton beam.

After cracking of CH_3^+-molecules and stripping into protons and carbon ions simultaneous proton and carbon beam operation (C^{6+}) in the post stripper has been enabled. For further poststripper acceleration the Alvarez dc quadrupole gradients were adjusted to an average A/Z-value of 1.35, sufficient for proton- (A/Z = 1) and C^{6+} (A/Z =2) operation. Avoiding strong scattering effects for the proton beam a relatively low stripper target density is required. In contradiction fully stripped carbon ions can only be achieved by high target densities. For 2021 and 2022 user runs simultaneous high intensity proton and carbon operation at UNILAC based on a sufficiently balanced target thickness could be first time carried out successfully.

SUMMARY AND OUTLOOK

The UNILAC serves as heavy ion accelerator since 1975. An R&D-program started seven years ago with the goal to operate UNILAC with high intensity proton beams until the dedicated FAIR proton linac is available. Since 2016 UNILAC can provide for up to 3 emA high brilliance proton beam) at a maximum beam energy of 20 MeV.

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2×10^{11} protons per second could be achieved at SIS18 extraction. Taking the achieved beam current, emittance and energy into account the UNILAC can provide for up to 1.5×10^{12} protons per second [6-9]. An advanced and simplified UNILAC-proton operation at a synchronous phase $\Phi s \approx -57°$ high intensity proton beam operation has been established. Simultaneous high intensity proton/carbon (6+) operation from a single ion source has been made available for user operation since 2021 [10, 11]. Simultaneous operation at maximum proton and C^{6+}-intensity is facilitated when the pulsed hydrogen gas stripper is put into operation.

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