HIGH CURRENT PROTON BEAM OPERATION AT GSI 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 [1]. The primary proton beam has to be provided by a 70 MeV proton linac followed by two synchrotrons. The new FAIR proton linac [2] will deliver a pulsed proton beam of up to 35 mA of 36 µs duration at a repetition rate of 4 Hz. The recent GSI heavy ion linac (UNILAC) is able to deliver world record uranium beam intensities for injection into the synchrotrons, but it is not dedicated for FAIR relevant proton beam operation. In an advanced machine investigation program it could be shown, that the UNILAC is able to provide for sufficient high intensities of CH_3-beam, cracked (and stripped) in a supersonic nitrogen gas jet into protons and carbon ions. This advanced operational approach results in up to 2 mA of proton intensity at a maximum beam energy of 20 MeV, 100 µs pulse duration and a rep. rate of 4 Hz. Recent linac beam measurements will be presented, showing that the UNILAC is able to serve as a proton FAIR injector for the first time, while the performance is limited to 17% of the FAIR requirements.

INTRODUCTION

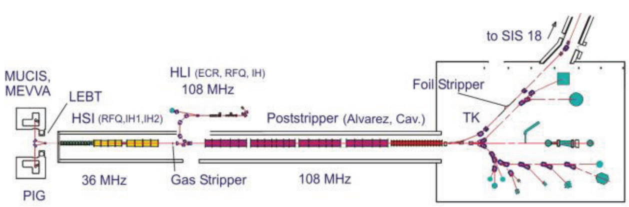

Figure 1: Schematic overview of the GSI UNILAC and experimental area.

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, consisting of 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 $\beta = 0.155$. In the transfer line (TK) to the synchrotron SIS 18 a foil stripper and another charge state separator system can be used. To provide the highest heavy ion beam currents (15 emA, U^{28+}), as required for the FAIR project, the GSI-HSI must deliver up to 18 mA of U^{4+} ions [3]. 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) comprising an RFQ and an IH-resonator to 1.4 MeV/u. The HLI as well as the HSI serve in a time-sharing mode for the main drift tube linac.

The new FAIR proton linac 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 room temperature 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 [2]

final energy	70 MeV
pulse current	70 mA
protons per pulse	$7 \cdot 10^{12}$
repetition rate	4 Hz
transv. beam emittance	4.2 µm (tot. norm.)
RF-frequency	325.224 MHz

The use of RF-coupled CH-cavities (<35 MeV) and single CH-cavities (35-70 MeV) is proofed to be advantageous for a compact and efficient linac design (Fig. 2). Commissioning of the new proton linac is envisaged for end of 2018.

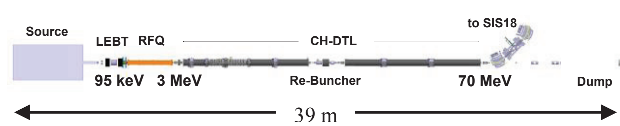

Figure 2: Layout of the FAIR-proton linac.

Recently an advanced investigation program at the existing UNILAC was successfully pushed to deliver high intensity proton beams (up to the UNILAC space charge limit) for a dedicated experimental program at SIS18. In this frame CH_3^+-beam operation with a MUlti Cusp Ion Source (MUCIS) was established. Besides efforts were made for careful machine optimizations in all UNILAC sections, aiming in a high proton beam transmission and highest beam brilliance.

Special focus of investigation efforts was the gas stripper- and charge seperator-section performance, where the molecules are cracked into protons and carbon ions and the separated high brilliance proton beam is matched to the Alvarez-DTL. proton beam acceleration and succesful transport via the 120m transfer line to the SIS18 depends mainly on the accurate set up of the RF-controls of the Alvarez high power supplies, operated at very low RF-power.

MACHINE DEVELOPMENT

The MUCIS source [4] is operated with methane (CH_4) gas while a high-current CH_3^+-beam (2.3 emA) is delivered to the HSI. Due to the huge emittance in the LEBT only 50% of the CH_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 40%. Anyway, due to the increased HSI design limitations for the CH_3^+-beam, 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 allows for proton beam operation at the design (space charge) limit of the poststripper linac (Fig. 3). 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%, only limited by the narrow aperture of a bending dipole inside transfer line.

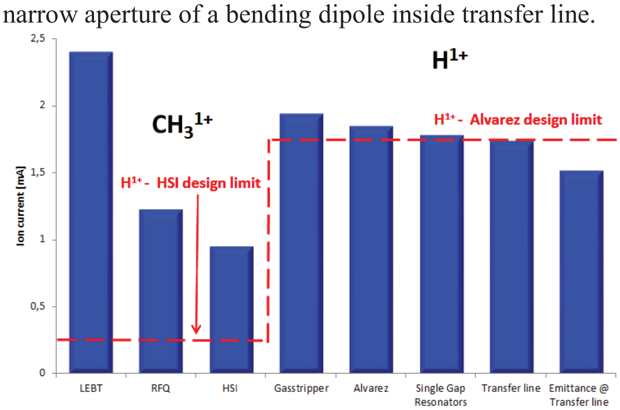

Figure 3: Measured beam current along UNILAC and transfer line to the SIS18; proton design limit was reached in the post stripper section.

Ion Source

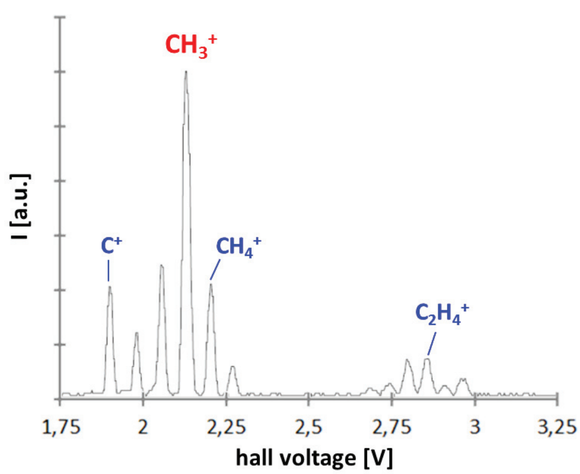

Figure 4: Optimized mass spectrum for CH_3^+-operation with the MUCIS.

The production of a CH_3 molecule beam has been performed with MUCIS ion source from methane gas with a duty cycle of 2 Hz and a pulse length of 1 ms. The plasma chamber of MUCIS is equipped with an external magnetic coil, that allows to increase the plasma density in the extraction region and results in higher extracted beam current. The spectrum of extracted beam is rather complex and contains several different molecule species (including higher order alkane chain) (Fig. 4). However it was possible to maximize the output of CH_3^+ ions by tuning the operation parameters of the ion source. Unfortunately the operation with methane gas causes a contamination of the ion source with carbon tinsels, limiting the operation lifetime of the source to 8-10 days. After that period a complete service of the ion source including cleaning of the extraction system is necessary.

Gas Stripper

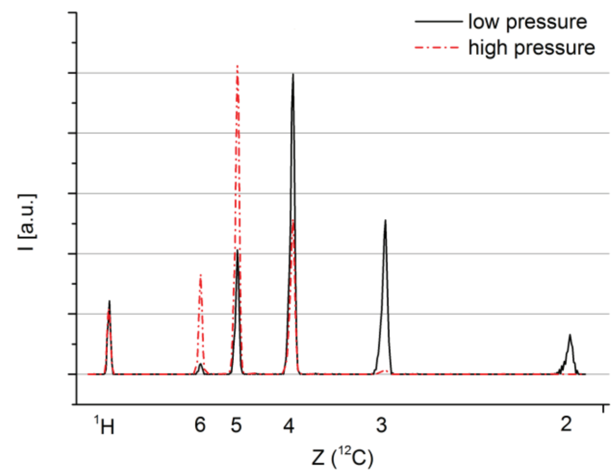

Figure 5: Gas stripper spectrum of the CH_3^+-beam from the HSI. Above a threshold (black) the proton beam intensity is independent on the N_2-target density, while the carbon beam could be optimized for higher Z (red).

The gas stripper section [5] is located between prestripper (HSI) and poststripper linac (Alvarez). In the supersonic N_2-gas jet the CH_3^+-molecule 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. 5) shows a proton fraction, which is (above a certain threshold) independent on the density of the supersonic nitrogen gas jet target. While the average charge of the carbon spectrum depends on the target density: A maximum at $Z = 4$ for lower gas pressure and at $Z = 5$ 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.

Post Stripper

The RF settings of the RF-amplifiers and their controls have been scaled and optimized for proton operation. This means that due to the very low output power the rise time of the RF pulse could be increased significantly. In the RF-signal forwarded by the high power amplifier a

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considerable beam load disturbance at the power plateau is detected and compensated by the fast LLRF control. While the beam is entering the cavity, the cavity impedance is decreased and in consequence the low level control system regulates the RF-amplifier to a higher forwarded RF-power and compensates the beam-dependent impedance.

Beam Measurements

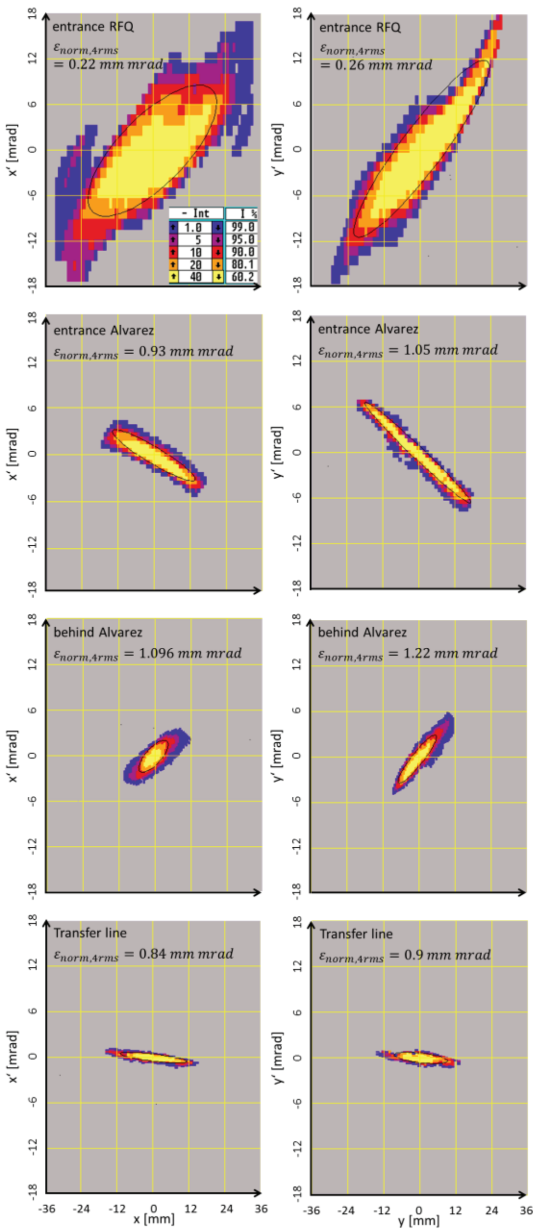

Figure 6: Measured high current proton beam emittance.

The high current transverse beam emittance was measured with high resolution in all section of UNILAC and transfer line (Fig. 6). The transverse high current emittance growth inside entire Alvarez section could be minimized for 17% only. Even though transmission loss was observed in the transfer line to the SIS18, beam brilliance has been kept constant during transport of the high current beam (Fig. 7).

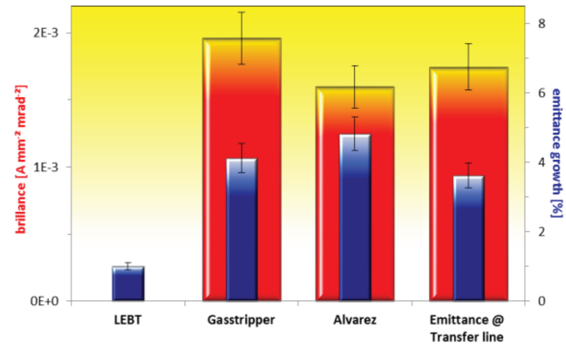

Figure 7: High current emittance growth and beam brilliance measurements along UNILAC.

OUTLOOK

Besides optimizing the high current proton beam performance for the ongoing GSI experiment program, the UNILAC is able to serve as a high performance proton injector for FAIR-commissioning and for first pbar experiments as a redundant option for the FAIR proton linac injector. For this, the UNILAC was operated in a high energy mode (20 MeV), breaking the recent proton intensity record for FAIR operation (Table 2)

Table 2: Comparison of FAIR proton injector options [6]

E [MeV]	**70**	**11.4**	**11.4**	**20**	**20**
I [mA]	35	1	2	1	2
$\varepsilon_{x,y\,(4\cdot rms)}$ *[mm mrad]*	7/8	7/8	7/8	3/3	3/3
γ	1.07	1.01	1.01	1.02	1.02
β	0.37	0.15	0.15	0.2	0.2
$\beta^2\cdot\gamma^3$	0.17	0.02	0.02	0.04	0.04
Space charge limit (N)	5.8e12	8.6e11	8.6e11	1.5e12	1.5e12
SIS100 (part./cycle)	1.7e13	1.2e12	2.3e12	1.5e12	2.8e12
SIS100 (relative)	100%	7.1%	13.5%	8.5%	16.7%
SIS18 MTI (N)	6.0e12	4.1e11	8.2e11	5.1e11	1.0e12

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