Measurement of UNILAC and SIS18 proton performance

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***Abstract*—On July 16th 2016 the UNILAC and SIS18 proton performance has been measured. Due to scheduled maintenance works of the UNILAC's rf-system, the post-stripper energy was restricted to 5.9 MeV and accordingly the beam quality suffered considerably from the interruption of the periodic focusing system. This limitation will not be any longer in future beam times. Six single-gap resonators were used for acceleration to 10.7 MeV. After an optimization of the multi-turn injection $1.2 \cdot 10^{11}$ protons were extracted form the SIS18.**

I. INTRODUCTION

The aim of the measurement was to determine the UNILAC and SIS18 proton transmission as well as to optimize the multi-turn injection (MTI) to fill SIS18 up to the intensity limit. Space charge is a major intensity limitation for synchrotrons expressed by the tolerable space charge tune shift

$$\Delta Q_{sc} = \frac{N_{sc} Z^2 g_f}{2\pi \beta^2 \gamma^3 A B_f \epsilon}. \quad (1)$$

The space-charge intensity limit N_{sc} can be enhanced by increasing the injection energy. Therefore is has been proposed to increase the SIS18 injection energy for protons to 20 MeV by means of the single-gap resonators. The goal of an optimized MTI is to reach the intensity limit

$$N_{sc} = m \frac{I}{qf} \quad (2)$$

by a large gain factor m (e.g. multiplication factor of injected current I), thereby not to exceed acceptance and loss limits. f is the revolution frequency at injection energy and $q = Ze$ the ion charge. Unfortunately, an increase of the injection energy leads to a lower injected intensity per turn due to the higher revolution frequency. To reach the higher space charge limit and to compensated, the revolution frequency effect a larger injected current or gain factor is required. Both demand an enhanced injector brilliance

$$B = \frac{I}{\epsilon}. \quad (3)$$

As smaller the injected emittance ϵ is, the higher the gain factor m gets [1]–[3], whereby the adiabatic damping through acceleration slightly relax the brilliance requirements. A normalized UNILAC brilliance of 4.8 (2) $mA/\mu m$ is required to fill SIS18 up to the space charge limit at 20 MeV (10.7 MeV) [4].

Table I
COMPARISON OF THE MEASURED AND ESTIMATED BEAM PARAMETERS [4].

	Estimation	Measurement
UNILAC		
E [MeV]	20	10.7
$\bar{I}$ $[mA]$	3	0.71
phy. ϵ_x $[\mu m]$	3	9.2
norm. B_x $[mA/\mu m]$	4.8	0.5
SIS18		
SC-limit	$1.5 \cdot 10^{12}$	$8 \cdot 10^{11}$
Injection gain factor	22	11
Transmission	0.95	0.6
Output particles per cycle	$1.4 \cdot 10^{12}$	$1.2 \cdot 10^{11}$

II. RESULTS

In the MUCIS ion source $CH3^+$ molecular ion beams were produced, which have been cracked (and stripped) in a supersonic nitrogen gas jet into protons and carbon ions. The protons were accelerated up to 5.9 MeV along the post-stripper DTL. Currently the rf-system of the fourth post-stripper cavity is upgraded. Accordingly the full output energy of 11.4 MeV was not available. However, 10.7 MeV could be achieved with the single-gab resonators. The fact that the last two post-stripper cavities could not be rf-powered lead to an interruption of the periodic focusing scheme, which in turn rose significant dilution of the transverse and especially the longitudinal beam quality. This limitation will not be any longer in future beam times. Accordingly, the results of this report are not so much representative for the anticipated performance in the future.

For an injection energy of 10.7 MeV the space charge intensity limit in the SIS18 for protons is around $8 \cdot 10^{11}$ particles for a tolerable space charge tune shift of $\Delta Q_{sc} = 0.5$. After an optimization of the multi-turn injection $1.2 \cdot 10^{11}$ protons were extracted from the SIS18. Table I shows the comparison between the measured and estimated beam parameters [4]. The nominated UNILAC brilliance was by a factor of 10 and the SIS18 transmission by a factor of 1.5 lower than required for the option of using the UNILAC as a proton injector for FAIR with 25% of the design intensity.

Figure 1 illustrates in detail the UNILAC proton transmission. The main reasons for the large decrease of the brilliance between entrance to the RFQ and the entrance to the post-stripper are transmission loss in the RFQ, poor matching to the IH-DTL along the MEBT, a non-periodic focusing along the IH-DTL, and finally an increase of the proton beam emittance from Coulomb-explosion during the cracking of the $CH3^+$

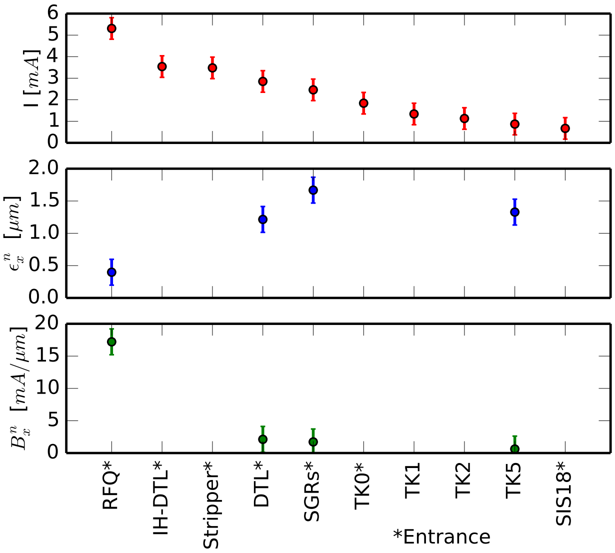

Figure 1. UNILAC proton transmission (Top: Current; Center: Emittance; Bottom: Brilliance)

molecules. Concerning the performance of the RFQ and the MEBT, corresponding upgrade measures have been proposed to the management since 2013. Further loss in brilliance along the transfer to the SIS18 is driven by the large longitudinal emittance after the post-stripper. This emittance is imposed by longitudinal mismatch from the limited post-stripper output energy and by the following acceleration along six single-gap resonators.

Figure 2 shows that with the physical emittance of $\epsilon_{4,rms} = 9.22\ \mu m$ a gain factor of $m = 11$ was achieved. Optimization of the SIS18 multi-turn injection was very difficult as the injected beam had a very low rigidity. Accordingly, many devices were operated very close or even below the limit of the specified stability range. In consequence, marco-pulse fluctuations with an averaged current of about $\overline{I} = 0.7$ mA occurred. A reduction of emittance and coincident increase of the gain factor were reached through beam collimation in the transfer line. The average current after collimation was $\overline{I} = 0.5$ mA. As Figure 3 indicates, this time an enhancement of extraction intensity through beam collimation as shown in [5] could not be achieved. The low SIS18 proton transmission of $T = 0.6$ is also visible in Figure 3. An increase of vertical beam size with a simultaneous decrease of horizontal beam size has been observed during the first milliseconds of the SIS18 cycle, see Figure 4. The cause for this is unknown.

III. CONCLUSIONS

The measured beam quality at 2016 for molecular beams at the SIS18 injection is not sufficient to reach the SIS18 space charge intensity limit at 10.7 MeV. Two out of five post-stripper cavities were not rf-powered due to scheduled upgrade works on the rf-systems. As expected the beam quality was significantly compromised from these circumstances. This limitation will not be any longer in future beam times. The source of the SIS18 increase of vertical beam size after injection need to be investigated and the SIS18 transmission

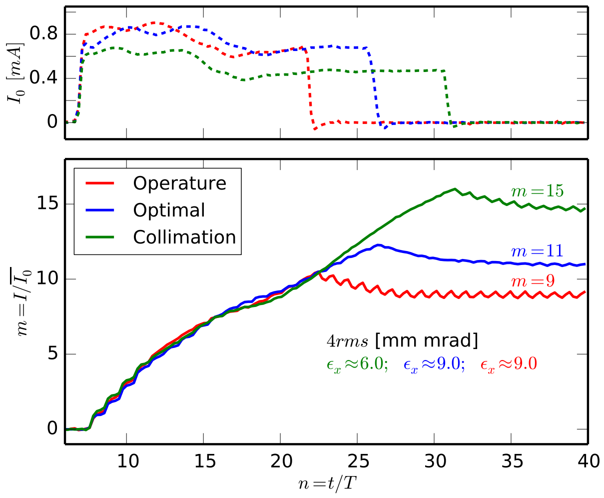

Figure 2. gain factor through the MTI (Top: The TK-Marco-Puls. Bottom: gain factor)

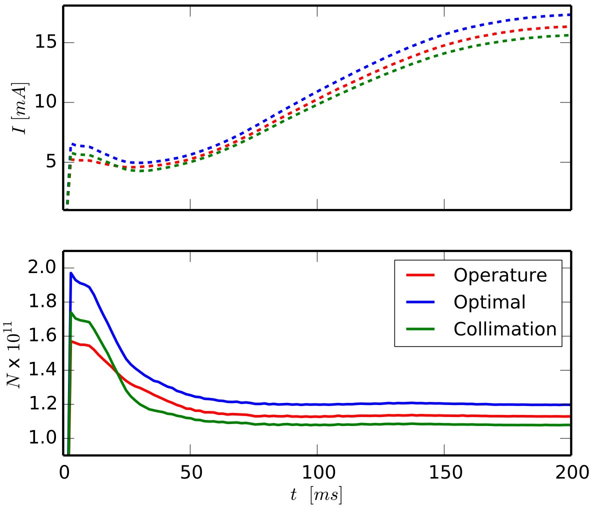

Figure 3. SIS18 proton transmission (Top: Current; Bottom: Particle number)

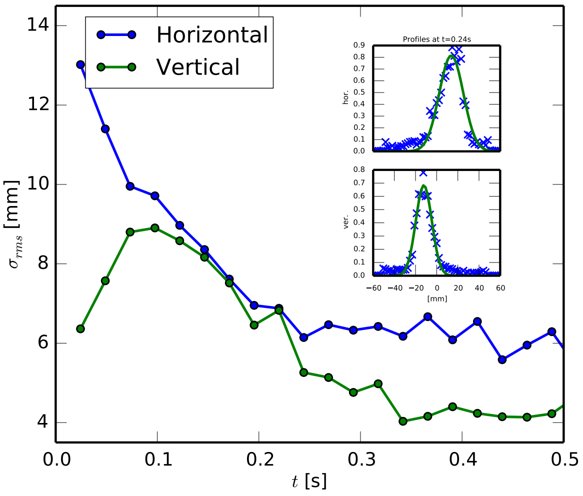

Figure 4. Beam size development (Inserted: Vertical and horizontal beam profiles at t=0.24s)

must be improved. This is important to reach 25% of the FAIR intensity with the UNILAC as injector.

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