COMPUTER SIMULATIONS OF A HIGH CURRENT PROTON BEAM AT THE SILHI-LEBT

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Abstract

For the injection into the future proton LINAC for FAIR the ion source and the low energy beam transport system have to deliver a 100 mA proton beam with an energy of 95 keV at the entrance of the RFQ within an acceptance of 0.3 π mm mrad (norm., rms). A 2-solenoid focussing system is foreseen as an injection scheme into the rf-accelerator. The beam parameters of the SILHI ion source and the 2-solenoid low energy beam transport (LEBT) setup at CEA/Saclay fulfill these requirements. Therefore joint emittance measurements for various beam parameters have been performed at the end of the LEBT in 2005. This contribution presents the computer simulations of the ion source extraction and LEBT, which supplemented these measurements using the KOBRA3-INP computer code in order to study the influence of space charge effects. These simulations have been performed for different solenoid settings and for different space charge compensation degrees.

INTRODUCTION

For the new international Facility of Antiproton and Ion Research (FAIR) the existing Universal Linear Accelerator (UNILAC) and heavy ion synchrotron (SIS18) will serve as an injector [1]. A dedicated proton LINAC is projected within FAIR which fulfills the demands on the beam brilliance for the proton beam injection into the SIS18. The design beam energy is 70 MeV and the beam current is 70 mA; a more detailed description is given in [2]. In order to achieve these design goals one requirement has to be fulfilled: the ion source and the LEBT have to deliver a 100 mA proton beam with an energy of 95 keV within an emittance of 0.3 π mm mrad (norm., rms). At CEA/Saclay the SILHI ion source and extraction with its subsequent 2-solenoid LEBT set up fairly meets these demands [3]. The ion source delivers a beam current of 110 mA with a proton fraction of 95 % at a beam energy of 95 keV. End of 2005 a joint beam measurement campaign had been carried out in order to investigate the high current beam parameters and the matching to the RFQ. The beam emittance was measured with a slit-grid device. These measurements have been compared to ion beam simulations using the KOBRA3-INP code [4].

EXTRACTION SYSTEM AND LEBT

The geometry of the extraction system and the applied potentials are given in [5]. The extracted ion beam had been calculated taking into account the measured charge state distribution of the ion source beam (95 % protons, 5 % H_2^+). For the calculation the whole beam line (total length 5.1 m, beam pipe diameter 140 mm) had been divided into five parts providing high accuracy in the simulation in a reasonable time:

1. extraction system
2. drift/first solenoid
3. drift with limiting apertures (steerers, current transformer, 75 mm in diameter)
4. drift/second solenoid with aperture (60 mm in diameter)
5. drift.

Additionally the input parameter such as the degree of space charge compensation of the ion beam could be changed along the beam line section by section.

The two identical solenoids have a maximum flux density (B1, B2) of 260 mT on the beam axis. The geometrical length is 0.5 m (see Fig. 1) [3,6].

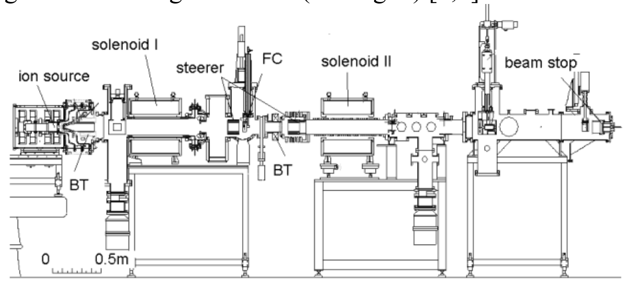

Figure 1: Schematic drawing of the SILHI-LEBT [3].

In a first step the space charge compensation degree had been varied by replacing the real current by an effective (net) current which is 0.0 up to 0.3 times the full beam current. This corresponds to a space charge compensation degree of 100 % and approximately 70 %.

Secondly a different model, the beam plasma model, had been applied. This model takes into account an electron density with its maximum at beam potential exponentially decreasing according to a decreasing potential to the beam edge [4].

The beam emittance is calculated at the slit position (0.9 m behind the second solenoid).

CALCULATION RESULTS

Fig. 2 is showing the simulation of the ion source extraction. The ion beam at the end of the extraction is assumed to be fully space charge compensated. Its emittance pattern yields an emittance of approximately 0.2 π mm mrad (norm., rms, 90 %) behind the last ground electrode. This particle distribution was taken as an input for all following simulations. The large divergence angle of 50 mrad is necessary to inject a broad proton beam into the first solenoid that enters the second solenoid as a broad parallel beam which can be focussed with large convergence angles of ±70 mm, sufficient for RFQ-injection.

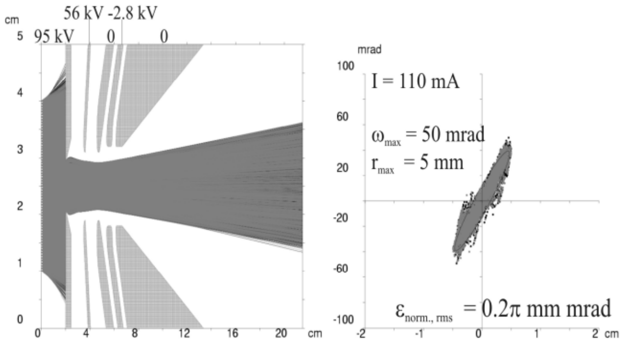

Figure 2: Extraction system, trajectory plot (left), emittance pattern (right).

In this case a magnetic flux density B1 of the first solenoid had been set to 129 mT, the second solenoid had been set to 215 mT.

In Table 1 the main simulation results are compared to the measurements of ion beam current, divergence angle, beam radius, emittance for the proton fraction (norm., rms, 90 % in simulation), and the Twiss parameter α. The measurement results are displayed in bold letters (norm., rms, 95 % in experiment).

It turned out that there is no satisfying agreement between experiment and simulation if the net current (corresponding to the degree of space charge compensation) is kept constant along the beam line:

1. Regarding the proton fraction all these simulations result in divergence angles much too large compared to the measurement.
2. The same applies for the beam radii while the ion beam currents are too low caused by particle losses at the limiting apertures in the third section; losses which are smaller in the zero current case.
3. The solution with zero current even shows an upright emittance figure of the H_2^+ ions instead of a convergent one.
4. No beam emittance growth occurs.

A possible reason for these disagreements might be that the space charge compensation degree is changing along the beam line. According to the conclusions drawn in [6] this fact had been considered by an ion beam which is only partially compensated within the solenoids (denoted by an asterisk) and fully compensated outside yielding the result given in Tab. 1.

For this case the beam plasma model had been applied as well. The result is marked in grey (90^b is denoting a space charge compensation degree of about 90 %).

Table 1: Measurement and simulation data; B1 = 129 mT; B2 = 215 mT; net cur.: net current; I: ion beam current; ω_i: divergence angle of protons and H_2^+; r_i: beam radii; $\varepsilon_{norm,rms}$: normalized rms emittance; d: divergent (α<0); c: convergent (α >0); f: focus (α =0); *: space charge in the solenoids only; ^{b}: beam plasma model

net cur.	**I mA**	**ω_1 H_1 mrad**	**r_1 mm**	**ω_2 H_2 mrad**	**r_2 mm**	**$\varepsilon_{norm,rms}$ πmm mrad**
meas	**60**	**70 d**	**40**	**35 c**	**12**	**0.48**
0.0	60	79 d	51	39 f	3	0.18
0.1	34	79 d	47	29 c	8	0.18
0.2	23	77 d	45	29 c	8	0.19
0.2^*	34	74 d	46	34 c	5	0.2
90^b	60	70 d	43	30 c	9	0.43

Both models yield a good agreement between the measurement and calculation concerning the divergence angles, beam radii, and the currents, while the rms emittance matches better for the beam plasma model. The calculated and measured phase space distributions are given in Fig. 3.

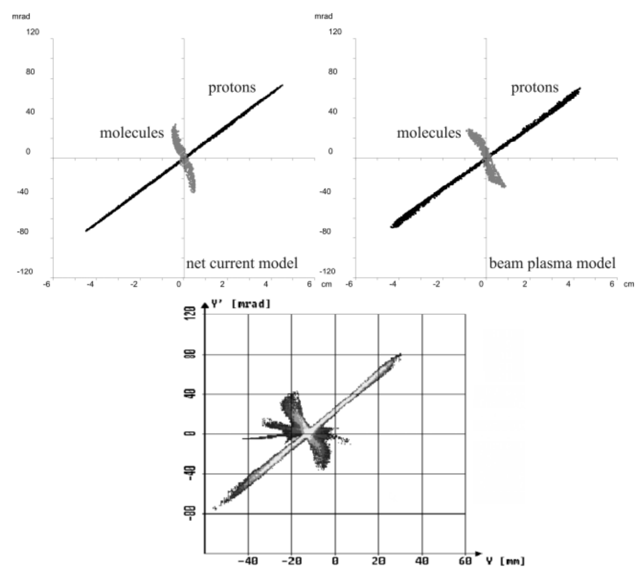

Figure 3: Calculated and measured phase space distributions: net current model (left), beam plasma model (right), parallel beam after solenoid 1 (B1 = 129 mT) and subsequent focussing after solenoid 2 (B2 = 215 mT); measurement (lower).

Fig. 4 is showing the emittance (protons only) at the proposed position of the RFQ input radial matcher. The emittance fits to the RFQ requirements: a focussed proton beam with a convergence angle of ±70 mrad; the emittance of about 0.43 π mm mrad is approximately 60 % above the acceptance of the RFQ, the current is 60 mA only limited by the apertures in the beam line.

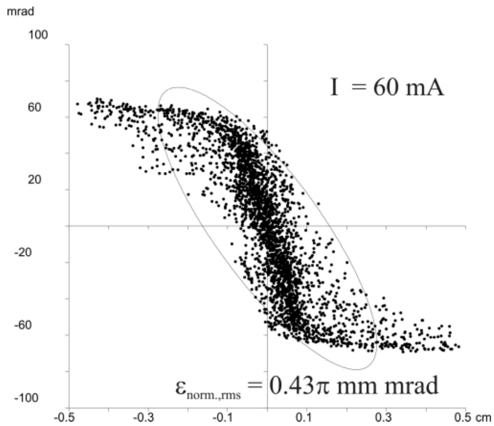

Figure 4: Emittance pattern for RFQ injection according to the beam plasma model.

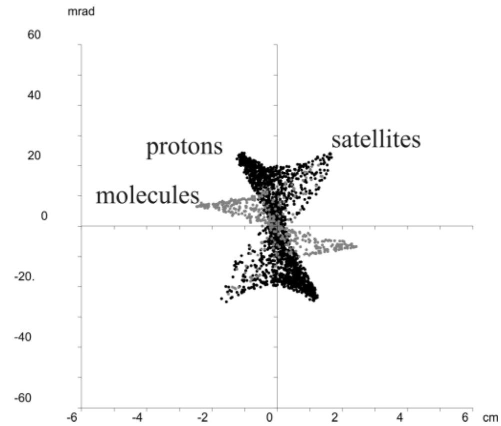

Figure 5: Emittance pattern with "Satellites", B1 = 129 mT, B2 = 114 mT.

DISCUSSION AND OUTLOOK

These presented simulation scenarios had been adapted to provide an optimum agreement to the beam emittance measurement with reasonable physical models, i.e. with an ion beam which is only partially space charge compensated within the solenoids. The phase space distribution of the proton fraction is close to the one in the measurement. The "bone" shape is due to the space charge forces which act on the beam edge region considered in the beam plasma model. This "bone" shape is responsible for the larger rms emittance compared to the net current model and fits well to the measurement. The aberrations of the H_2^+ fraction are caused by a large radius of this fraction in the first and second solenoid where the space charge forces act on the beam edge. These aberrations are transformed into the subsequent drift section leading to a narrow H_2^+ beam with aberrations. The beam emittance according to the net current model is less than half of the measured on, the aberrations of the H_2^+ fraction is due to space charge forces and optics in the solenoid.

Considering these facts, the beam plasma model within the solenoids seems to be the most reasonable model so far.

The ion beam is only partially space charge compensated within the solenoids due to electron confinement at the beam axis leading to an overcompensation and a less compensated beam outside [7].

This is responsible for the appearance of another ion population (given the name "satellites" in [6]) because of the strong focussing force near the beam axis. This had been considered in a test case by introducing a potential in the near axis region created by a cylindrical electron beam 10 mm in diameter (see Fig. 5).

Besides a more sophisticated treatment of space charge compensation according to the beam plasma model for other solenoid settings further simulations including an electron distribution within the solenoids will be performed in the near future.

It can be concluded from the simulations that a two solenoid beam line is able to provide a convergent focussed proton beam with typical RFQ injection parameters such as a high convergence angle of ±70 mrad, and a proton current of 100 mA within a suitable emittance. Therefore a 2-solenoid beam line (adapted to the demands of the future proton linac) might be a promising option for the RFQ injection at the future proton linac at GSI.

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