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Transport of a high brightness proton beam through the Munich tandem accelerator

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ABSTRACT

Basic requirement for ion microprobes with sub-μm beam focus is a high brightness beam to fill the small phase space usually accepted by the ion microprobe with enough ion current for the desired application.

We performed beam transport simulations to optimize beam brightness transported through the Munich tandem accelerator. This was done under the constraint of a maximum ion current of 10 μA that is allowed to be injected due to radiation safety regulations and beam power constrains. The main influence of the stripper foil in conjunction with intrinsic astigmatism in the beam transport on beam brightness is discussed.

The calculations show possibilities for brightness enhancement by using astigmatism corrections and asymmetric filling of the phase space volume in the x- and y-direction.

1. Introduction

A beam with a high brightness B is the basic requirement for running an ion microprobe with sub-μm beam focus in order to fill the small transversal phase space volume that is accepted by a usual ion microprobe (acceptance) with enough ion current I for the desired application. For a rectangular beam profile the transversal emittance, ε, is given by $\varepsilon = \Delta x \Delta\theta_x \cdot \Delta y \Delta\theta_y$ when Δx and Δy are the beam sizes at a beam focus (crossover) and $\Delta\theta_x$ and $\Delta\theta_y$ the divergence at this point. In this case beam brightness is, as normally done when neglecting relativistic effects, defined by

$$B = \frac{I}{\varepsilon E} = \frac{I}{\Delta x \Delta\theta_x \cdot \Delta y \Delta\theta_y E}. \quad (1)$$

with E being the kinetic energy of the incident ions. Influences on beam brightness from longitudinal components of the phase space volume are not considered further throughout the paper.

Since the beam spot size of a high demagnifying lens is normally limited by lens aberrations [1], the beam spot size can be minimized by reducing the acceptance. However, beam brightness has to be increased in the same amount as the acceptance is reduced to keep a constant ion current I that is required for a certain application.

In order to enhance beam brightness we installed a multicusp ion source for negative hydrogen ions manufactured by HVEE [2] at the Munich 14 MV tandem accelerator with a lab-tested beam brightness of $B = 27$ μA mm^{-2} mrad^{-2} MeV^{-1} at 30 keV with an emittance size of $\varepsilon = \pi \cdot 0.81$ mm $\cdot$ 1.15 mm $\times\ \pi \cdot 7.6$ mrad $\cdot$ 8.3 mrad and a current $I = 465$ μA at the exit of the source [3]. At the high energy side of the accelerator in front of the ion microprobe SNAKE, however, we measured a beam brightness of $B_{exp} = 2.3$ μA mm^{-2} mrad^{-2} MeV^{-1} at a beam energy $E = 20$ MeV.

In this paper we discuss beam transport through the tandem accelerator in order to understand the different contributions to the loss of brightness and to get knowledge on how beam brightness can be optimized.

According to Liouville's theorem the phase space volume of an ensemble of particles is constant as long as only conservative forces, especially static electric or magnetic fields, are involved. Thus, beam brightness B remains constant in case the transversal phase space volume εE is decoupled from the longitudinal one. In this case the brightness as defined in Eq. (1) won't change between injection and experiment under normal beam transport conditions. However, the shape of the transversal phase space filled by the ion beam can change under conservative forces. If the phase space volume does not fill the complete acceptance of the microbeam, the brightness averaged over the acceptance of the microprobe is reduced. In addition, the beam suffers from small angle scattering in the stripper foil of the tandem accelerator, where Liouville's theorem is no longer valid and the phase space volume is increased.

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Both effects on an overall brightness reduction can be minimized if the phase space filled by the ion beam is maximized, as discussed in this paper.

However, filling the acceptance of the accelerator with the high brightness beam of the multicusp ion source gives a total beam current of about 1 mA, although only 10 μA are allowed to be transported through the Munich 14 MV tandem accelerator due to beam loading, slit heating and radiation safety constraints.

Thus, the aim of the paper is to find the phase space volume of an injected ion beam under the constrain of maximum ion current that leads to an optimum brightness and thus an optimum ion current at the ion microprobe SNAKE. In order to obtain a quantitative description beam transport calculations through the Munich tandem accelerator have been performed (Section 2) including the main source of brightness loss through small angle scattering in the stripper foil of the tandem accelerator (Section 3).

2. Beam brightness behind a tandem accelerator system

2.1. General description of the brightness

The beam brightness as defined in Eq. (1) gives the beam current I normalized to εE that is proportional to the phase space volume filled by the beam. In general, the beam current will not be uniformly distributed over the accepted total phase space. The brightness will depend on the considered point in the four dimensional phase space and becomes a local value: $B = B(x, y, \theta_x, \theta_y)$.

During beam transport a point of the four dimensional emittance $(x_0, y_0, \theta_{x,0}, \theta_{y,0})$, e.g. at the injection of the tandem, is transformed to another point $(x_1, y_1, \theta_{x,1}, \theta_{y,1})$, e.g. at the object aperture of a microprobe. According to Liouville's theorem the local brightnesses won't change as long as only conservative forces are involved: $B(x_0, y_0, \theta_{x,0}, \theta_{y,0}) = B(x_1, y_1, \theta_{x,1}, \theta_{y,1})$.

The average brightness B_{out} of the beam within the acceptance of a microprobe ε_{exp}, is the average of the local beam brightness $B(x, y, \theta_x, \theta_y)$ over the accepted phase space:

$$B_{out} = \frac{\int_{\varepsilon_{exp}} B(x, y, \theta_x, \theta_y) dx dy d\theta_x d\theta_y}{\int_{\varepsilon_{exp}} dx dy d\theta_x d\theta_y} = \frac{I}{\varepsilon_{exp} E}. \quad (2)$$

It is the figure of merit in order to determine the total current I accepted by the microprobe at the energy E at a given acceptance ε_{exp}. For a legible discussion we use in this paper the brightness that is normalized to the injected brightness B_{in} with

$$B_{norm} = \frac{B_{out}}{B_{in}} \quad (3)$$

A change of the (local) brightness happens in the stripper foil of a tandem due to stripping efficiency and small angle scattering. Both processes are discussed in Sections 2.3.1 and 2.3.2.

2.2. Description of beam transport

2.2.1. Low energy stage of the tandem-accelerator

The beam transport system through the Munich MP-8 tandem is very well described in [4] and we only want to discuss the main elements that are required for the simulation of the beam parameters. These elements are shown in Figs. 1 and 2a. With two close

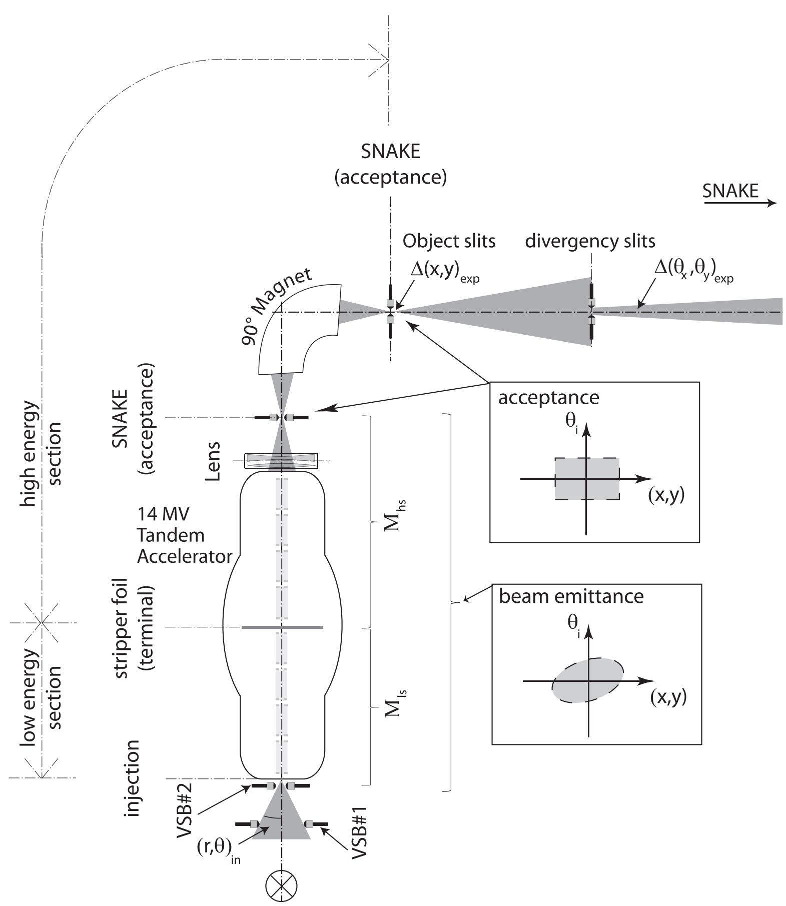

Fig. 1. Illustration of the principal setup on the Munich tandem accelerator with its main optical elements from injection to the experiment SNAKE.