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TECHNIQUES FOR HIGH CURRENT ION BEAM DIAGNOSTICS†

T. WEIS, R. DÖLLING, P. GROSS, J. POZIMSKI, G. RIEHL, J. WIEGAND and H. KLEIN

Institut für Angewandte Physik der Johann Wolfgang Goethe Universität, Postfach 111932, D-6000 Frankfurt am Main, Germany.

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Sophisticated systems for the transport and the acceleration of low energy, high current ion beams are necessary for a driver for heavy ion inertial confinement fusion. The components of the accelerator system as well as the space charge of the ion beam itself may exhibit field nonlinearities, which give rise to emittance degradation. These losses of beam quality should of course be reduced as far as possible. While the nonlinearities of external fields can be investigated mainly by numerical methods, the properties of the internal space charge fields of compensated and uncompensated beams can only be examined by means of experimental diagnostic techniques.

During the last three years several techniques for destructive and non-destructive beam diagnostics have been further developed and tested at the Institut für Angewandte Physik, Frankfurt. Retarding field spectrometers and 127° electrostatic energy analyzers are the nondestructive tools used to measure the integral or differential energy spectra of residual gas ions created and expelled from the beam; they allow the evaluation of potentials of the transverse space charge of uncompensated and space-charge-compensated beams. By means of an external transverse electron beam (typically 1 keV, 1 μA) even non-destructive determination of the distribution of the radial charge density of high intensity ion beams is possible. With the aid of a multifunctional profile and emittance measurement system, which, in addition to our standard slit-to-grid mode, can be operated now in a point-to-grid mode, a better resolution of the transverse emittances and the transverse density in real space can be achieved.

1 INTRODUCTION

Degradation of beam quality measured by the increase of rms-emittance is caused by unlinearities of fields acting on the ion beam. Especially at low energies, the main contribution to possible emittance increase is believed to originate from the re-arrangement of the transverse distribution of the ion density, thus minimizing the nonlinear field energy of the ions in their own space charge field[1,2,3]. Therefore it is strongly recommended to focus attention especially on the low energy part of an accelerator system (where the field energy is high) to keep the growth of overall emittance as low as possible.

The precise measurement of transverse emittances, along with the evaluation of radial distributions of ions and compensating electrons as well as the overall degree of compensation, is necessary to gain information on field nonlinearities acting on the system, whether caused by external or internal fields.

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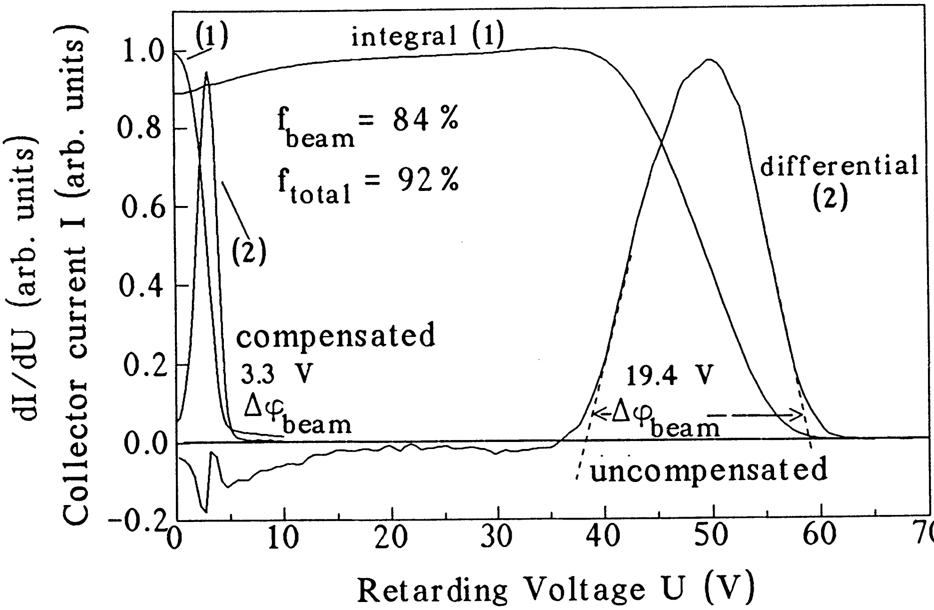

FIGURE 1 Integral (1) and differential (2) energy spectra obtained from a residual gas ion spectrometer for a compensated and decompensated 10 keV, 1.5 mA He^+ beam. The evaluated degrees of compensation f vary according to the different definitions of f (for explanation see text).

2 ELECTROSTATIC ENERGY SPECTROMETERS FOR RESIDUAL GAS IONS

The collisions of beam ions and residual gas atoms give rise to plasma build-up. In the absence of external electric fields, the low energy electrons are trapped by the positive beam potential (in the case of a positive beam) thus lowering the acting space charge forces significantly. The residual gas ions created via ionization or charge exchange are expelled from the beam, the final energy (measured by the spectrometer) depending on the location of creation and the acting space charge potential[4,5].

Typical integral output signals versus retarding voltage are given in Figure 1 together with the calculated differential energy distributions. The system allows for a quick evaluation of the degrees of compensation by comparing corresponding measurements on the same beam in the uncompensated and compensated case. The highest energy present in the distribution has been gained by an ion created on the beam axis and corresponds to the overall beam potential, ϕ_{total} (beam axis-ground potential at outer wall), whereas the lowest energy is linked directly to the beam potential at the edge of the beam, ϕ_{edge}. The difference of the potential inside the beam ($\Delta\varphi_{\text{beam}} = \varphi_{\text{total}} - \varphi_{\text{cedge}}$), which is responsible for the acting space charge forces on the beam, can be compared for uncompensated and compensated transport and leads to the degree of compensation f_{beam}

$$f_{\text{beam}} = 1 - \Delta\varphi_{\text{beam, compensated}}/\Delta\varphi_{\text{beam, uncompensated}}.$$

The total degree of compensation f_{total} can be defined analogously by

$$f_{total} = 1 - \Delta\varphi_{total,\,compensated}/\Delta\varphi_{total,\,uncompensated}.$$

Both values of f are identical only if no electrons are located outside the beam area.

Determining the radial distributions of the potential and of the space charge density, respectively, is in principle possible, but suffers from uncertainties concerning the angle of observation (aperture diameter 8 mm) and secondary processes such as secondary emission of electrons and ions in the device. Therefore the operation of the spectrometers is applicable for ion energies ranging from as low as approximately 2 eV up to a few hundreds of eV with an uncertainty of $+/-1$ eV.

Our retarding field spectrometers are very compact (60 mm diameter, 80 mm length) and can be used even at locations with little available mounting space.

A compact 127° deflection electrostatic spectrometer has also been built and tested. The device directly gives the differential energy spectra of the ions with enhanced energy resolution. First attempts have been made to correct the measured energy spectra with respect to energy resolution and spectrometer properties, and an evaluation of the transverse space charge distribution shows promising results.

Using Helmholtz-like coils in order to make sure that very low energy electrons are not deflected by stray fields, even electrons with energies <10 eV escaping from the beam could be detected.

Both types of spectrometers are used routinely as non-destructive diagnostic devices in our high current beam transport experiments[3,6].

3 TRANSVERSE ELECTRON BEAM PROBE

An electron beam probe (typical values: 1 keV, 1 μA) has been developed for the measurement of the space charge potential and charge density as functions of radius for intense ion beams under uncompensated and compensated conditions. The electron beam probe (EPB) uses an external transverse electron beam, which is deflected by the electric field of the ion beam[7,8,9]. The EPB consists of a Pierce-like electron gun and an electrostatic deflection system to obtain a variation of the transverse coordinate with respect to the ion beam. The probing beam is detected with a resistor coated plate of ceramics by analyzing two partial detector currents (position resolution: 0.2 mm, time resolution: 5 μsec). The device is computer controlled and allows for automatic scanning of the ion beam. A typical deflection characteristic is shown in Figure 2. For a given beam the degree of compensation can easily be evaluated by the comparison of the deflections for large transverse coordinates of the electron beam with respect to the ion beam in the compensated and uncompensated cases.

For small deflection angles we were able to perform an Abel inversion of the measured deflection characteristics[8,10] giving the space charge potential and the net charge density (ions and compensating electrons e.g.) as a function of radius. Figure 3 shows the radial distribution of the net charge density of a compensated beam calculated from the deflection characteristic of Figure 2. The beam is hollow with a

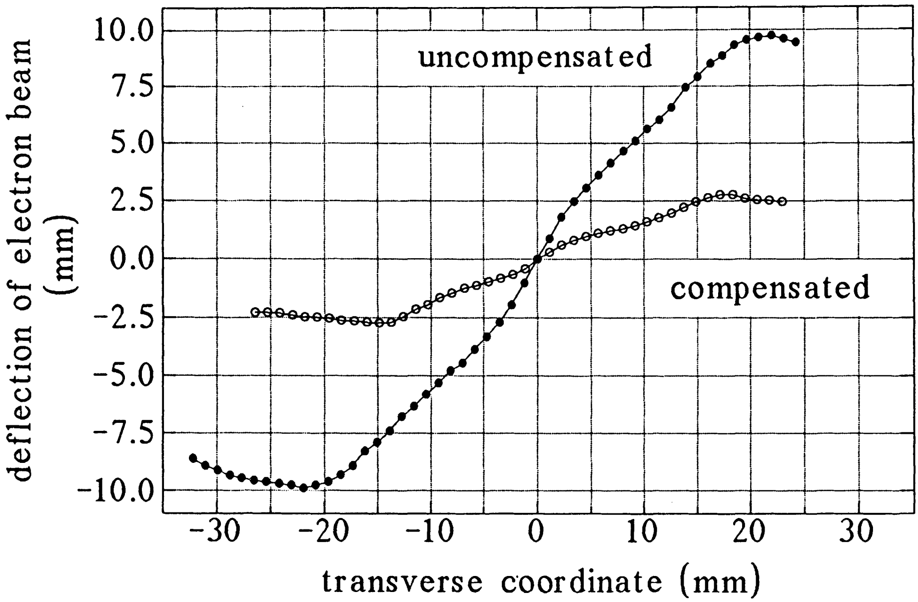

FIGURE 2 Deflection characteristic for a compensated and decompensated Ar^+ beam (0.8 mA, 10 keV).

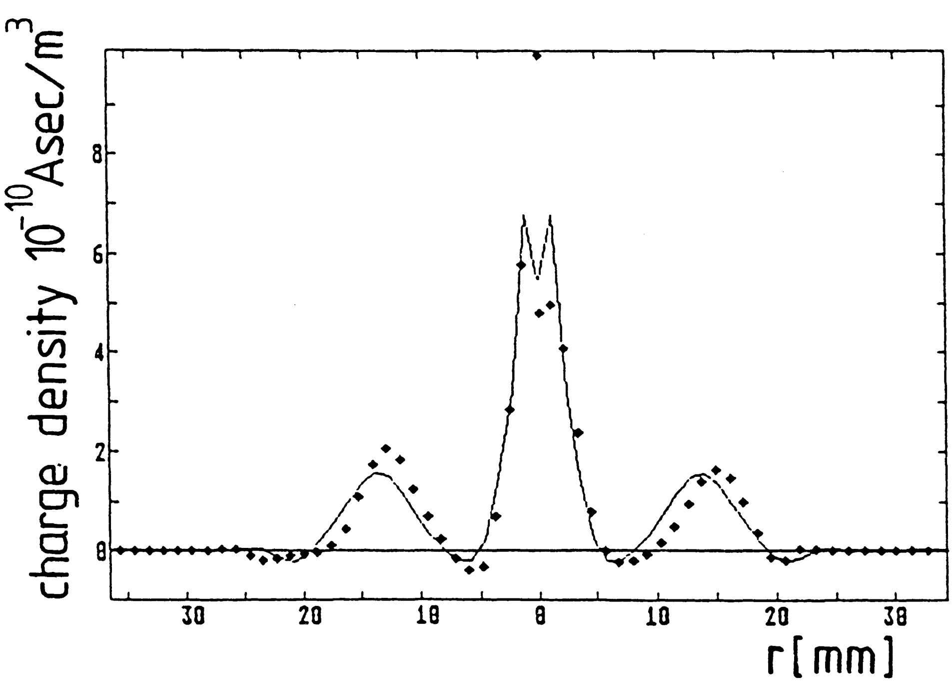

FIGURE 3 Radial distribution of the net charge density calculated from the deflection characteristic for the compensated beam shown in Figure 2 (points). The curve is a fit to calculated values obtained from a symmetric deflection characteristic (average deflection at specific radius r). The values near the center of the peak as well as the central dip of the curve are uncertain due to the used Abel transformation.

sharp center peak due to aberrations of an Einzel lens system. The distribution of the compensating electrons causes regions of net negative charge density between the maxima and outside the beam area. Due to the typical properties of an Abel inversion the obtained values near the beam center are uncertain. The comparison of measurements under compensated and decompensated conditions even allows for the separate evaluation of ion and electron distribution respectively.

The device is capable of resolving time dependent processes such as the evolution of increasing degrees of compensation at the front end of a beam macropulse. The rise time of compensation has been measured giving ionization cross sections that are in excellent agreement with data from the literature[7,8,11,12].

Up to now the limited resolution of our detector system allows only for low electron energies (1 keV) and the application of the EPB is not possible for the analysis of almost fully compensated beams. Moreover, the EPB can be used at the moment only at particularly prepared test stands where all possible precautions have been taken to reduce magnetic stray fields. An improvement of the detector resolution will either allow for a better analysis of compensated beams or higher electron energies in order to reduce the existing problems with magnetic stray fields.

4 MULTIFUNCTIONAL PROFILE AND EMITTANCE MEASURING DEVICE

Standard slit-grid emittance and profile measurement devices give only basic information on the transverse ion beam current distributions such as $I(x)$, $I(y)$, $I(x, x')$ and $I(y, y')$ due to the integration over the y and x direction respectively. Our existing device has been extended to allow for slit-to-grid as well as point-to-grid measurements, which, due to a better local resolution, give an enhanced physical insight into the 3-dimensional phase spaces $I(x, x', y)$ and $I(y, y', x)$. From the obtained distributions $I(x, x', y_i)$ and $I(y, y', x_i)$, at different locations x_i and y_i respectively, all 2- and 1-dimensional subspaces (standard emittance $I(x, x')$ and ion density $I(x, y)$, for example) can be deduced, as indicated in Figure 4. From the distributions $I(x, x')$ and $I(y, y')$ obtained by slit-to-grid methods however a reconstruction of the density in real space $I(x, y)$is not possible.

Figure 5 shows a typical example of a 2-dimensional ion current distribution in real space. It is calculated from measurements of $I(x, x', y_i)$ at different locations y_i.

Up to 4 slit/profile harp combinations may be installed to 6 stepping motor driven UHV feedthroughs. The profile currents of one harp are switched by a multiplexer to the 60-channel current amplifier. Motor and electronics are controlled by an 8 bit microprocessor system with digital I/O boards. A 68000 PC handles the interactive dialogs, the measurement procedure and data storage as well as comfortable data display and evaluation[13]. The slits are made of tantalum, molybdenum or stainless steel, and cooled versions for beam powers up to 6 kW are available. An optional kicker in front of the system may increase the measurable beam power up to approximately 1 MWatt.

The device is easy to operate and, especially when operated in the point-to-grid

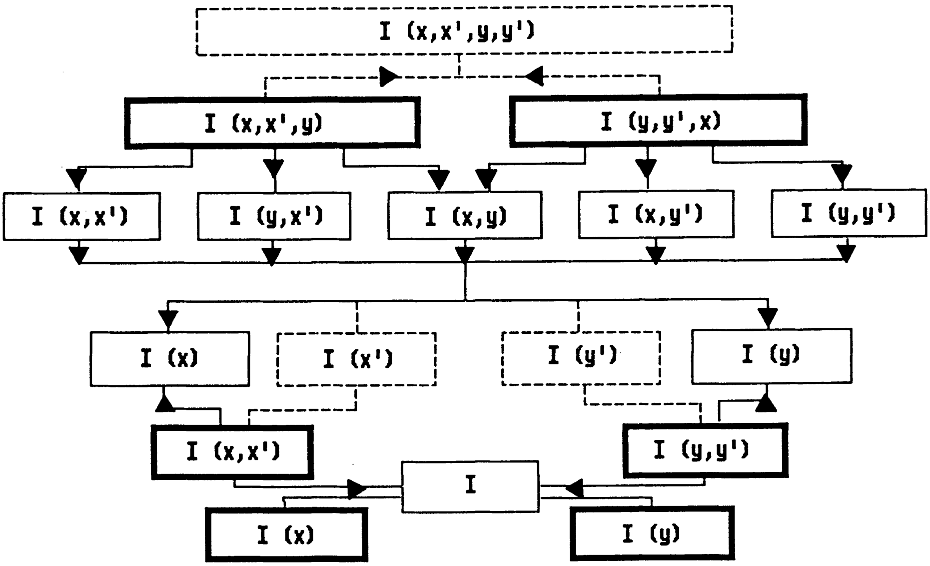

FIGURE 4 Survey on phase space distributions, which may be measured (fat) or calculated from measurements.

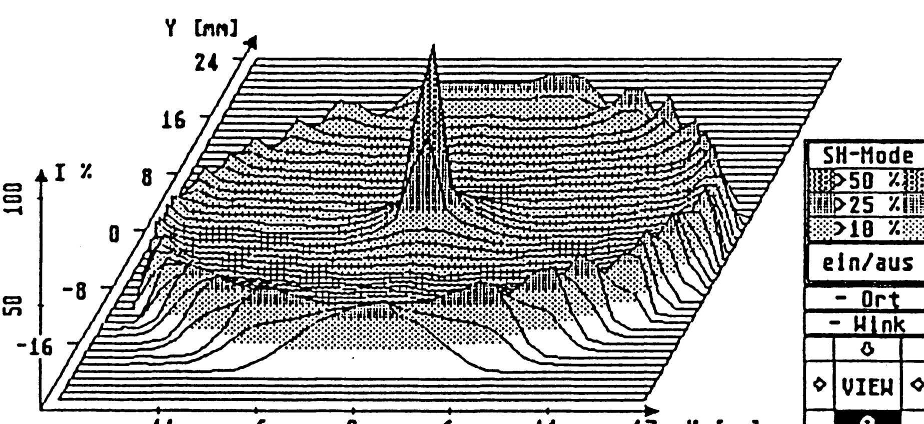

FIGURE 5 Radial density distribution of an intense He^+ beam behind a magnetic lens with strong aberrative effects. The distribution is calculated from measurements of $I(x, x', y_i)$ at different locations y_i.

mode, allows a detailed evaluation of emittance growth, for example, corresponding changes of ion density distribution, and occurring field unlinearities.

5 CONCLUDING REMARKS

The methods mentioned above offer an attractive supplementation to commonly used diagnostic techniques for high current ion beam behavior. The development of measuring devices for beam potentials and corresponding electron and ion density distributions in strong magnetic fields (e.g., those of solenoids and quadrupoles) is a task for the future. Beam analysis carried out with electric plasma probes in a magnetic solenoid have shown poor results thus far.

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