ANALYSIS OF THE ELECTRON BEAM SCANNING METHOD FOR BEAM PROFILE MONITORING

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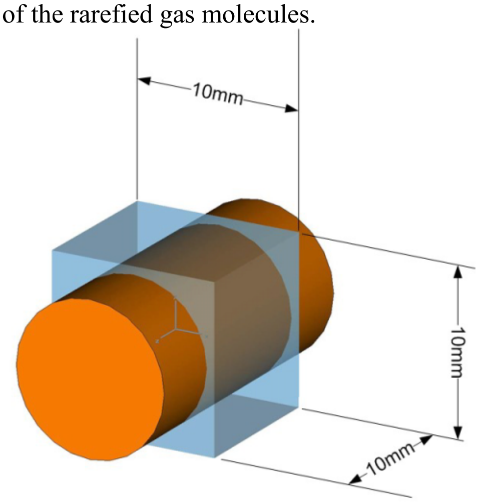
Abstract

The method of beam profile monitoring using a scanning electron beam is analyzed. The estimation of overall method performance characteristics such as sensitivity, spatial resolution, frequency bandwidth etc. is given.

INTRODUCTION

The state of the modern accelerator art requires high quality support from the beam diagnostic community. New applications of circulating beams need precise control of the beam shape during beam cooling. High beam intensities also call for optimization of injecting procedures. All these factors are making a high performance of non destructive profile measurements very desirable during injection, accelerating, cooling and storing operations. The residual gas monitor (RGM) provides a good possibility for heavy ion beam profile investigation with high spatial ***or*** fast time resolution [1]. The probe media which interacts with beam particles is a set of residual rarefied gas molecules in the beam pipe. The efficiency of the RGM directly depends on the density of the rarefied gas molecules.



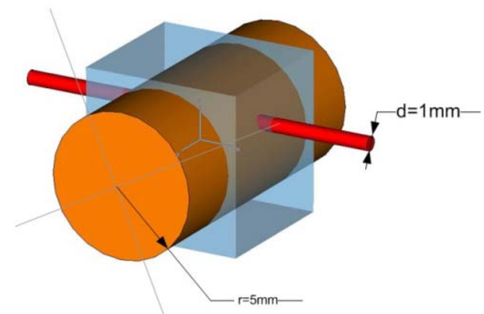
$$N = n_0\cdot\pi\cdot r^2\cdot h\cdot\frac{P}{P_{atm}} = 2.7\cdot10^{25}\cdot\pi\cdot25\cdot10^{-6}\cdot10^{-2}\,\frac{10^{-9}}{760} = 2.8\cdot10^{7}$$

Figure 1: The residual gas monitor working region may consist of 28 Mio of rarefied gas molecules.

Figure 1 shows the 1cm^3 working area of a RGM which included about $3\cdot10^7$ molecules which may be ionized by accelerated ions.

GENERAL METHOD DESCRIPTION

Another idea to use particle by particle interaction is the detection of the scattered electrons. When the electron beam is directed through the ions as it is shown in Figure 2, some electrons may be deflected from its original trajectory by a collision with particular ions.



$$N_e = \frac{I}{e_0}\cdot\frac{2\cdot r}{V} = \frac{1}{1.6\cdot10^{-19}}\cdot\frac{2\cdot5\cdot10^{-3}}{5.9\cdot10^{6}} = 1.1\cdot10^{10}$$

Figure 2: A 100 eV, 1A electron beam brings into the impact volume 10^{10} particles.

A 5 mA electron beam brings into the beam crossing volume nearly the same number of particles as a residual gas under 10^{-9} torr pressure conditions does (shown on Figure.1.)

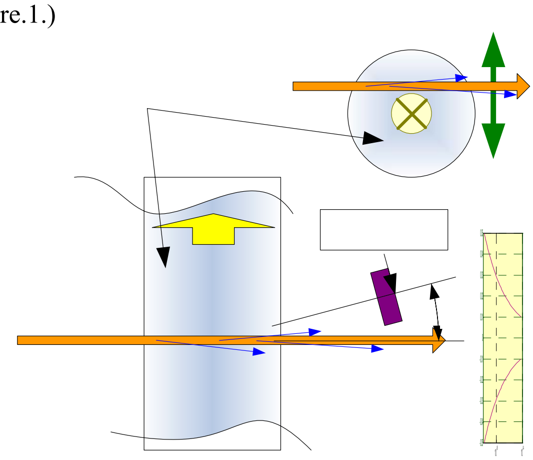


Figure 3: Simplified profile measurement layout.

The beam profile may be reconstructed by counting of scattered electrons in connection with the electron beam position as it is shown on Figure 3.

The *electron beam scanner* has some advantages compared to the residual gas monitor. It has a local character, electron beam parameters can be easily controlled and no external **E** or **B** fields in the ion beam line are required. The electrons have a velocity much higher than the residual gas ionization products have, therefore good timing resolution can be obtained even for longitudinal measurements.

SCATTERING PROCESS

The performance of the measurement process strongly depends on the number of scattered electrons. There are a few models of electron-ion collision mechanisms available and a lot of experimental data are collected for different kind of ions and a wide range of collision energies.

As an example Figure 4 shows some experimental data compared with simulation results of the complicated quantum Hartree-Fock model and classical Rutherford approximation [2].

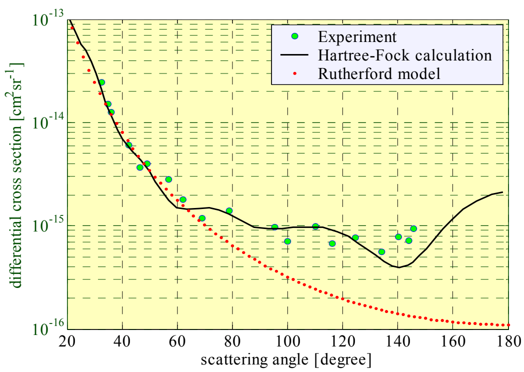


Figure 4: Differential cross section for the elastic electron scattering from Xe^{+6} ions[2].

The classical Rutherford formula for the differential cross section in the centre of mass coordinate system is

$$\frac{d\sigma}{d\Omega}=\left(\frac{Ze^2}{4\pi\varepsilon_0\cdot 4E_k}\right)^2\cdot\frac{1}{\sin^4(\theta/2)} \quad (1)$$

Here, Z is the charge number of the ion, e the elementary charge, E_k the kinetic energy of the impact electron and θ the scattering angle in radians. For the data shown in Figure 4 this formula gives well matched result for scattering angles lower 60 degrees.

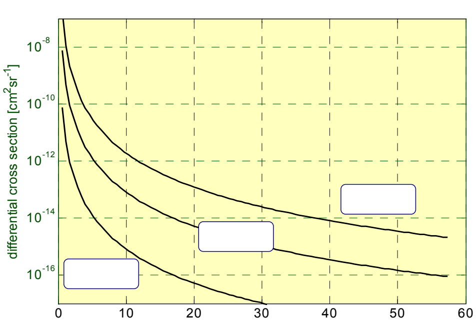


Figure 5: The dependence of the scattering angle on the impact parameter in the classical Coulomb model for Zi=6 and collision energies=0.02, 0.1 and 1keV.

To reach a high performance, much smaller scattering angles are used in the profile measurements. The Rutherford model can be successfully used to describe the electron's behaviour in this range of scattering angles. Figure 5 shows calculated cross sections in the centre of mass coordinate system for different impact energies and the ion charge number Z=6.

PROFILE MEASUREMENT

The electron beam with a diameter much smaller than the ion beam diameter is crossing the ion trajectories and some of the electrons are scattered due to the collisions with some ions. The key question is the performance of this method. The Rutherford approximation is used to estimate the performance of the scattered electrons detection method. The results are presented in the Table1.

Table 1: Profile measurement performance. D – the ion beam diameter, N_i – the number of ions in the ion beam, N – the number of registered electrons per turn., N_{RGM} – number of registered electrons(or ions) in RGM, N_{ADV} – the number of registered electrons in advanced mode (see below).

Ion energy	**D**	N_i	N_{RGM}	**N**	N_{ADV}
50MeV/u	10 mm	10^{10}	3.7	1.75	$6\cdot10^3$
1GeV/u	10mm	10^{10}	0.23	0.245	-
50MeV/u	1mm	10^8	0.04	0.17	60

This table shows three important cases: profile measurement at injection time, the case of maximum particle energy and the case of a cooled beam. All these examples are considered to be at the conditions of 5mA electron scanning beam. The diameter of the electron beam is 10 times smaller than the ion beam diameter. The electron energy is 1keV and the charge number of ions Z=6. The values are presented for horizontally scattered electrons. The electron detector is occupying 0.003 sr and is capturing electrons declined to 35mrad angle from the main electron beam direction in the laboratory coordinate system. For comparison the electron scattering method with residual gas ionization the results presented in [4] were used. The ionization conditions are 10^{-9} torr vacuum, rarefied hydrogen and 1cm length of the RGM active area.

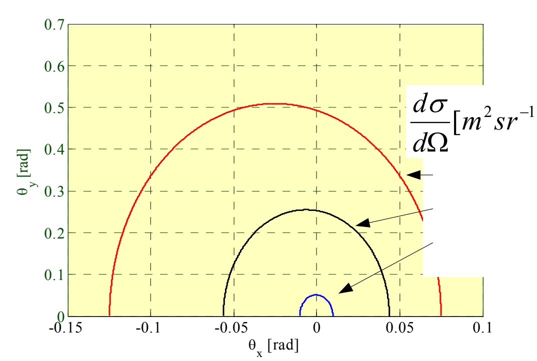


Figure 6: The lines of the equal differential cross sections for 50MeV/amu ion beam in the laboratory coordinate system.

Figure 6 shows the lines of equal differential cross sections in the 2D scattering angle's plane. The electrons have a higher probability to be scattered in the vertical plane than in the horizontal. But there are some disadvantages in using the vertically scattered electrons: for high intensity ion beams the electrons can be declined in the vertical plane by the cumulative space charge of the ions, and also the vertical divergence of the electron beam is not a free parameter. A spatial resolution requires an adequate high vertical divergence. So it is proposed to use horizontally scattered electrons for profile measurements.

The Rutherford formula shows a strong differential cross section dependence on the impact energy. It is essential to try to improve the measurement by equalizing ion and electron velocities as it is shown on Figure 7.

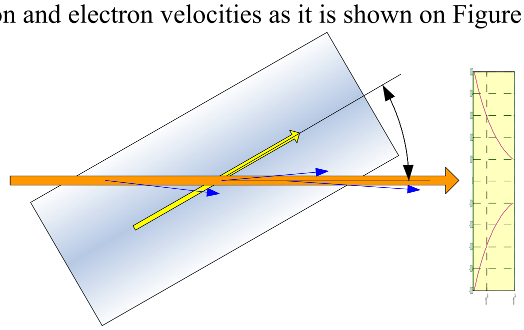


Figure 7: Probe electron beam directed in a small angle to the ion beam to equalize ion-electron velocities on the low edge of the ion energies.

Though it is not practicable to make test electron energies variable to cover the full range of the ion beam velocities, but equalizing velocities for low energy ion beams gives a high performance to some interesting applications: detailed investigation of the injection time beam behaviour and high resolution, high dynamic range profile measurements during cooling processes.

Another way to improve this method performance is using electrons with smaller scattering angle. To get a benefit of the $\frac{1}{\sin^4(\theta/2)}$ component of the Rutherford formula an electron beam with small divergence is needed. Figure 8 shows the electron beam phase space evaluations. At the ion beam line the electron beam is expanded in horizontal plane and compressed in vertical one. So Liouville's theorem requires high divergence in the vertical plane and a small one in horizontal. Expanded up to 100 mm the electron beam has a divergence of about ±0.5 mrad. The detector covering $25 \cdot 10^{-8}$ sr can be placed in the 1.5mrad position. The Rutherford model gives for this case of about $6 \cdot 10^3$ electrons on the detector per ion beam turn (most right column of the table 1).

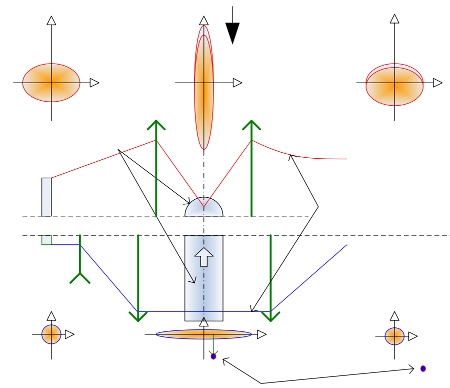


Figure 8: Phase space evaluations during probe electron beam transportation.

A high divergence (100mrad) in the vertical plane has an additional advantage. In some cases the ion beam space charge effect is strong enough even to be used for profile measurement [5]. As an example 10mrad maximal deflection angle due to the space charge is estimated in the conditions described for the table 1. The vertical plane is not used for scattered electron detection and the ratio 1:10 is admissible.

CONCLUSION

The non-intercepting beam profile measurements by using the *electron beam scanner with scattered electrons detection* can be used in the same situations as a residual gas monitors in the case of vacuum conditions better than 10^{-9}torr. The advanced mode of the measurement allows turn by turn profile registration for predefined ion beam energy. High velocity and low energy spread of the scattered electrons makes the longitudinal profile measurements also possible.

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