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Ion Beam Neutralization with Ferroelectrically Generated Electron Beams

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ION BEAM NEUTRALIZATION WITH FERROELECTRICALLY GENERATED ELECTRON BEAMS

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Abstract

A technique for ion beam space-charge neutralization with pulsed electron beams is described. The intensity of multiply-charged ions produced with a laser ion source can be enhanced or decreased separately with electron beam trains of MHz repetition rate. These are generated with ferroelectric cathodes, which are pulsed in synchronization with the laser ion source. The pulsed electron beams guide the ion beam in a similar way to the alternating gradient focusing of charged particle beams in circular accelerators such as synchrotrons. This new neutralization technology overcomes the Langmuir Child space-charge limit and may in future allow ion beam currents to be transported with intensities by orders of magnitude higher than those which can be accelerated today in a single vacuum tube.

Introduction

Nowadays high ion beam current intensities are required for all kinds of accelerators. This is also true for heavy-ion (HI) linacs and circular accelerators such as the future LHC at CERN [1]. The intensity is limited by the particle source or the technology of the accelerator system. Space-charge effects cause the most important problems in high-intensity charged particle accelerators. In conventional accelerators the beam travels in vacuum tubes and its space-charge forces are compensated by external magnetic focusing fields in the transverse direction and by electrical accelerating fields in the longitudinal direction. When the particles enter the relativistic regime, the Lorentz transformations for the focusing and accelerating fields show an increasing compensation of the transverse space-charge forces, but not of the longitudinal electric space-charge field components. Hence, the beam intensity in classical accelerators is limited by the technically feasible magnetic focusing (<10 T) and electric accelerating (<100 MV/m) fields. Space-charge forces are especially destructive at very low kinetic particle energy and for HI with high charge states. Nature shows that currents in the MA range and current densities more than 10^{10} A/cm^{2} can be transported in lightning and in high pressure gas or vacuum discharges. Such extreme current density values become possible because of the mutual space-charge and current compensation in the counter-moving electron and ion streams of the discharge plasmas. Several neutralization processes and techniques can be envisaged for increasing beam intensities in accelerators beyond the classical regime. In the past, space-charge neutralization has often been applied in high-intensity ion and electron sources and accelerators [2–5]. Passive or active neutralization techniques may be applied. A passive process is the self-neutralization of an intense electron [6], or ion beam [4] passing through a plasma or low-pressure gas. Reference [4] describes an example of the passive neutralization of an ion beam propagating through several accelerating grids, from which electrons are sputtered off and accelerated in the opposite direction. In passive neutralization modes the accelerated beam is the master of the process, attracting charged particles of opposite sign from the environment (for example a plasma or a low-energy electron source [3]). Active neutralization is characterized by external control over the accelerated beam. In this neutralization mode auxiliary beams of opposite charge can 'guide' the accelerated beam through different sections of the accelerator system. This paper describes the active space-charge neutralization of a beam of highly-charged HI, to increase selectively the intensity of the highest charge states compared to the case without neutralization. Pulsed electron beams are used to exert control over the accelerated HI beam.

Method, experimental set-up, results and conclusions

Whereas in the classical accelerator regime space-charge fields are generally equal to or smaller than the external focusing and accelerating fields, in a fully space-charge compensated high-intensity accelerator, space-charge forces would exceed the external electric and magnetic forces if neutralization were absent. Since a direct transition from a conventional scheme to a fully neutralized accelerator system is technically difficult, we envisage the application of space-charge neutralization at first in the critical sections of a classical accelerator system. The low energy sections of a classical accelerator usually form the most critical bottlenecks: the particle source, the initial drift tubes, and the very first accelerating sections. The method considered here aims to neutralize and to enhance a particular charge state from the whole spectrum of an HI beam and to 'suppress' all the other HI charge states. The neutralization, is achieved by intense, high-repetition rate electron beam pulses [5] which move in the same or in the opposite direction with respect to the HI beam, with differing absolute velocities. Intense electron beam pulses are generated in a gun with switched ferroelectric (FE) cathodes [7,8]. Recombination losses in such mutually penetrating beams can be considered negligible [9]. Ionization processes lead to an increase of the high-charge state population of the HI spectrum. By maintaining accurate control over the current intensity, the position, the diameter, the time-sequence and the synchronization of the electron beam pulses with the HI source, part of the HI beam is transferred through the neutralization section with increased intensity. The scheme shown in Fig. 1 exerts alternating gradient forces (focusing by the electron pulses and expansion by the HI space-charge) on the chosen HI beam part. If such a process, which is characterized by partial neutralization, is applied inside an HI source, such as a laser ion source (LIS), the fundamental mechanisms of charge and beam generation and the interaction mechanisms between the HI and electron beam pulses and the source plasma must be known, in order to efficiently control the neutralization. The application of partial neutralization inside a drift tube is easier. A well-suited accelerator section for neutralization is the first acceleration gap after an HI plasma source (LIS). The bunches of highly-charged HI generated inside the source self-neutralize with slow plasma electrons before, during, and after leaving the active source region of the LIS. Inside the first acceleration gap the HI have their accompanying electron cloud partially 'stripped off' because of the accelerating field. If behind that gap the net HI beam current exceeds the Langmuir Child (LC) equivalent limit, the HI blow up. Pulsed, repetitive electron beam neutralization in a critical section can maintain a much higher ion beam current in the transport channel than allowed by the LC limit. Technically the neutralization scheme near an accelerating gap is easier to perform than inside a LIS with its tiny target spot. A detailed description of the whole set-up (Fig. 2) is given in Ref. [10]. The main components are a small LIS with an Nd:YAG laser (5 ns pulse length), an electron gun with an FE cathode (Figs. 2 and 3) generating energetic, pulsed, focused, hollow electron beams, and beam diagnostics comprising an electrostatic ion analyser (EIA), a Faraday cup (FC), and a beam current transformer (BCT). The electron gun shown in Fig. 2 sends electron pulses in the direction of the LIS. The FE cathode has a 3 mm hole in the centre, which allows the ion beam to pass through the FE cathode into the analysing section of the system. The focusing and temporal synchronization conditions for the neutralization encounters of the electron and ion beam pulses near the first accelerating gap can be studied with an off-line electron gun (Fig. 3) which is equipped with a luminescent screen placed at a distance from the FE cathode corresponding to that of the FE cathode and the first accelerating gap.

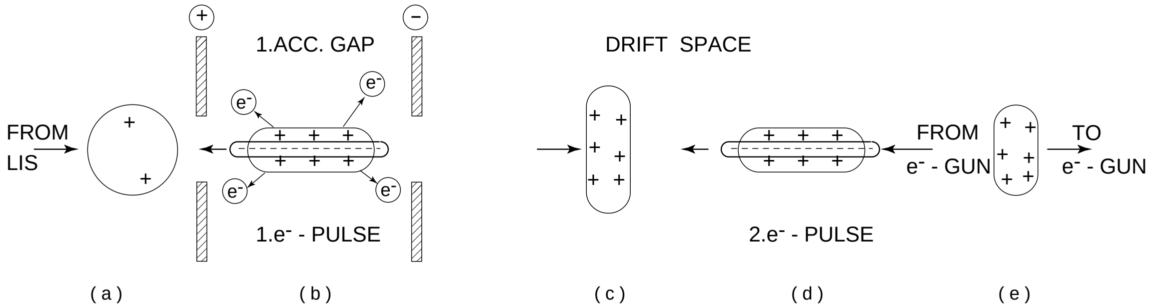

Fig. 1: Principle of ion beam space-charge neutralization with pulsed electron beams

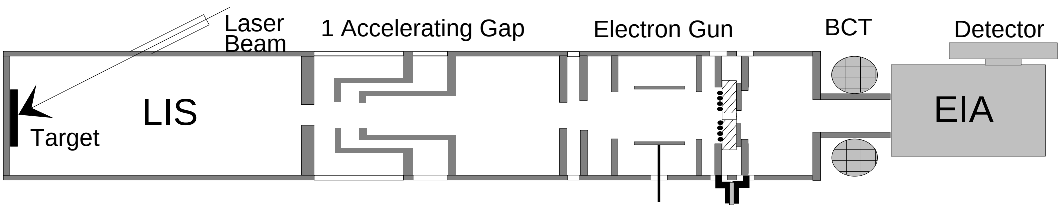

Fig. 2 Main experimental set-up

The LIS, together with the EIA, generate HI spectra in which the different charge states are well separated [10]. Furthermore the FE electron gun can produce high-rep-rate electron bunches which are accurately defined in space and time, and which can be easily synchronized with the laser pulse. Figure 4a shows the focusing of electron beams generated with an annular FE cathode emission grid in the off-line FE gun, and observed with a luminescent screen at the end of the gun. Figure 4b shows a double electron pulse with a spacing of 1 μs, the intensity and focal length of which can be varied in a controlled way. Figure 5 shows the intensity increase by a factor of 2 of the Al^{2+} energy spectrum, neutralized with a single electron pulse and measured with a photomultiplier behind the EIA and compared to the non-neutralized case. The synchronization conditions of the LIS and the FE gun were chosen in this case to cause neutralization to happen in the drift tube between the gun and the accelerating gap. Figure 6 shows the energy spectrum of charge-state Al^{7+} obtained with the EIA with electron bunches hitting the ions near the acceleration gap and in front of the LIS side of the FE gun.

The neutralization experiments described here and in Ref. [10], in spite of not being carried out in optimal conditions, have resulted in an intensity increase by a factor of two for Al^{2+} and four for Al^{7+} ions. For the highest charge states the relative increase can reach one order of magnitude. The accuracy and precision of the electron beam generation will allow a much stronger intensity increase to be obtained. These results could have important consequences not only for accelerators in high energy physics research, but also for inertial fusion oriented accelerator systems, as they show the way out of the dilemma of classical machines: the space charge limitation in an accelerator using vacuum as the transport medium. The application of the neutralization technique is encouraged in a real accelerator source and in the low-energy part of an HI linac. The method described permits d.c., RF and inductive acceleration in the non-neutralized sections, and even inductive acceleration in the neutralized sections, as well as the use of magnetic insulation and plasma lenses for fine-focusing ion beams.

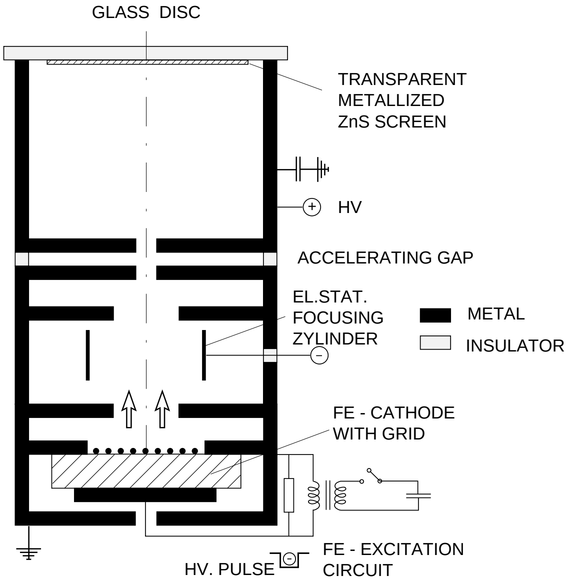

Fig. 3: Electron gun with ferroelectric cathode

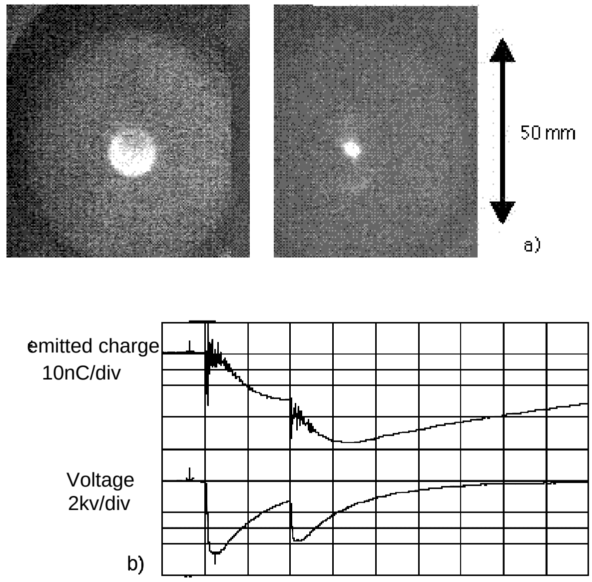

Fig. 4: a) Images from a luminescent screen of the focused and non-focused electron beam pulses. b) High rep-rate electron pulse current waveforms measured in the off-line electron gun

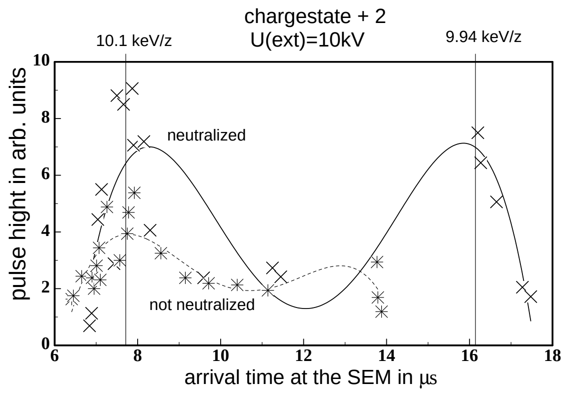

Fig. 5: Low-charge state ion beam enhancement by a factor of 2 with neutralization in the drift tube

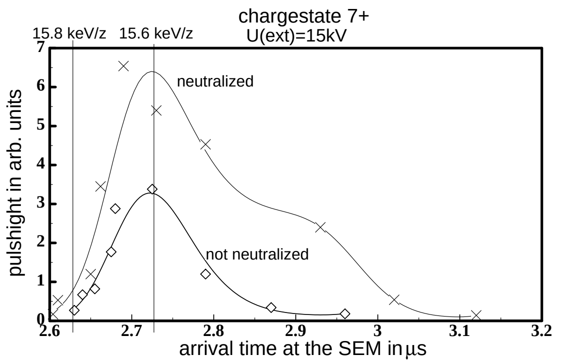

Fig. 6: Energy spectrum of Al^{7+} ions with and without space-charge neutralization near the accelerating gap

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