Vacuum-Spark Metal Ion Source Based on a Modified Marx Generator

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***Abstract*—The plasma-generating parts of ion sources including their power supplies are usually floated to high potential (ion extraction voltage), thus requiring great insulation efforts and causing high costs for high-energy ion beams. A new concept for pulsed ion sources is presented in which a single power supply is used to simultaneously produce the plasma and high extractor voltage via a modified Marx generator. Proof-of-principle experiments have been performed with high-current spark discharges in vacuum where multiply charged ions are produced with this Marx-generator-based ion source ("Magis"). Using "Magis," it has been demonstrated that pulsed ion beams of very high energies can be obtained with relatively low voltage. For copper, ions of charge states up to 7+ have been found whose energy was 112 keV for a charging voltage of only 10 kV.**

***Index Terms*—Ion-charge state distribution, ion sources, Marx generator, metal ion beams, plasma generation.**

I. Introduction

THE production of ion beams is generally done in two steps: 1) the material of interest is ionized so that a plasma is formed containing ions, free electrons, and neutrals, and 2) the ions are extracted from the plasma, commonly by using a three-grid system of the accel–decel type [1]. Examples for step 1) are Penning, dc magnetron, hot cathode filament, or RF gas discharges, or arc discharges in vacuum. Step 2) requires that the plasma potential is much higher than the potential of the beam and substrate, allowing the ions to become accelerated by the potential difference (extraction voltage). Therefore, the plasma-generating parts of an ion source including their power supplies are floated to high positive potential (or negative potential for negative ions). Ion sources consequently have at least two power supplies: one at elevated potential producing the plasma, and a second which shifts the potential of the first supply together with the extractor system. Insulation requirements for high ion energies (hundreds of kiloelectronvolts or higher) imply substantial difficulties and costs. In this paper, we report on the concept and proof-of-principle experiments showing that a single, nonfloating power supply can be used to produce a plasma at elevated potential.

Another basic idea presented in this paper is to increase the ion charge state in the plasma prior to extraction to obtain high ion energy at relatively low extraction voltage. The pulsed system serving for both plasma production and ion extraction is well suited to obtain a high-energy density in the plasma, resulting in multiply charged ions. As an example, we investigated repetitively pulsed, high-current discharges between metal electrodes in vacuum (vacuum sparks). High charge states have been observed spectroscopically in vacuum sparks. At very high currents (greater than 100 kA) and discharge energies (greater than 3 kJ), extremely high charge states such as H-like and He-like Ti and Fe have been observed in "hot spots" (see, for instance, [2]–[4]). These hot spots have a lifetime in the subnanosecond range, and there is no hope to extract these extremely charged ions to form an ion beam. A realistic goal, however, is to extract ions whose charge state is significantly higher than what is usually obtained in metal vapor vacuum arc (Mevva) ion sources. This is important because a gain in charge state leads to a proportionally higher ion energy for a given extraction voltage.

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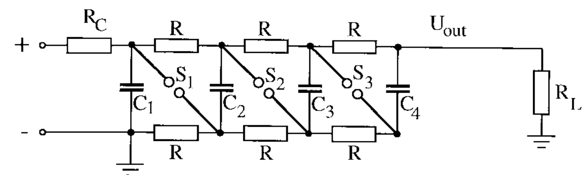

Fig. 1. Schematic of a four-stage Marx generator. R_C: charging resistor, R: stage-separating resistors, C_i: capacitors, S_i: switches (spark gaps), $U_{\rm out}$: output voltage; R_L: load.

II. Concept of a Marx-Generator-Based Ion Source ("Magis")

A Marx generator is a voltage-multiplying scheme proposed decades ago [5]. The idea is to charge capacitors C_i $(i = 1, 2, \cdots, N)$ for a voltage U_o and switch them in series to obtain a high voltage

$$U_{\max} = NU_o. \tag{1}$$

Equation (1) neglects losses; the number N, in practice, should not exceed 10 [6]. We describe the standard Marx generator (Fig. 1) in more detail because it helps in understanding the modified scheme of the ion source.

During charging, all N capacitors are electrically in parallel with one side at ground potential. It is important to note that all but the first capacitor are mounted insulated from ground, and that all capacitors are separated from each other by resistors. There is a switch S_i between the high potential side of capacitor C_i and the ground of capacitor C_{i+1}, with

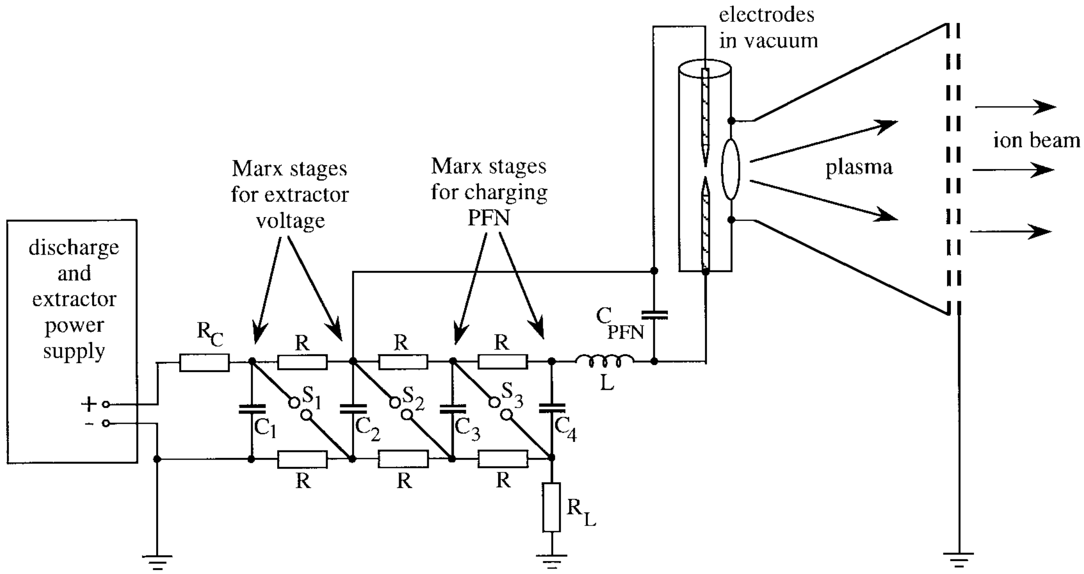

Fig. 2. Principal electrical scheme of "Magis." The pulse-forming network is symbolically represented by a lumped capacitor $C_{\rm PFN}$. L: inductive resistor (coil); the other notation is as in Fig. 1.

the counting index $i = 1, 2, \cdots, N-1$. For high-voltage applications, as in our case, spark gaps are commonly used as switches. Switch S_1 is triggered or set to break down first. The ground of C_2 shifts to the potential U_o and its high potential side to $2U_o$, causing an overpotential of $2U_o$ at spark gap S_2. Consequently, S_2 breaks down, shifting the ground potential of C_3 to $2U_o$ and its high potential side to $3U_o$, etc.

A novel Marx-generator-like scheme has been employed to generate a discharge plasma at elevated potential, thus allowing simultaneous plasma production and ion extraction. The principle of this Marx-generator-based ion source, "Magis," is explained for the case where four Marx generator stages are used (Fig. 2).

The two stages near the ground potential are exclusively used to shift the potential of the plasma by $2U_o$ above ground. The main function of the other two stages is to charge the capacitors of the pulse-forming network (PFN). The PFN represents the energy source for the discharge plasma. It can consist of discrete LC stages or a coaxial cable, strip line, etc.

The operation of "Magis" starts with the charging of all capacitors via a charging resistor R_c. The spark gaps are set in such a way that gap 2 breaks down first, causing all other spark gaps to trigger. After the breakdown of spark gaps 3 and 4, the energy stored in C_3 and C_4 is transferred to the PFN via the inductive load L. The voltage at the PFN is given by (neglecting ohmic losses)

$$U_{\rm PFN}(t) = U_o \frac{C_M}{C_M + C_{\rm PFN}} \left[1 - \cos\left(\frac{t}{\sqrt{L_c C_c}}\right)\right] \qquad (2)$$

where C_M is the series capacitance of the Marx capacitors used for charging the PFN, $C_c = (C_{\rm PFN} \cdot C_M)/(C_{\rm PFN} + C_M)$, and L_c is the inductance of the circuit. The charging of the PFN is terminated when a discharge starts in the discharge chamber (the discharge is a vacuum spark in our case).

Another function of the last two stages is to boost the plasma potential beyond the $2U_o$ coming from the first two stages of the Marx generator. The plasma potential is related to the potential of the electrodes; because they have approximately the potential $2U_o$ and $4U_o$, the plasma potential is in between these values. Its actual value depends on the plasma and the discharge circuit. Ideally, the PFN is terminated with an impedance-matching resistor, thus avoiding undesired oscillations of the discharge current and the associated plasma potential.

III. Proof-of-Principle Experiments

A "Magis" has been built following the principles described above. The plasma was produced by a pulsed high-current discharge in vacuum. The vacuum discharge was driven by either a simple high-voltage capacitor or by a six-stage PFN made from lumped elements (high-voltage capacitors and inductors); in both cases, the charging was done by a Marx-generator-like scheme as shown in Fig. 2. Another experiment is in preparation using a low-impedance high-voltage cable as the PFN. The maximum charging voltage was $U_o = 15$ kV. In our preliminary tests, we sacrificed the matching termination of the PFN in order to obtain high currents at relatively high impedance and relatively low voltage. The first tests were made with a simple capacitor as the "PFN." This capacitor formed an LC circuit with the inductance of the electrodes and their connecting cables. This has the advantage that a high-peak current can easily be achieved. The discharge current oscillates with a damping depending on the ohmic resistance of the circuit including the discharge plasma. A disadvantage is that the potential of the electrodes in the discharge chamber also oscillates, i.e., the extractor voltage is time dependent in this case [Fig. 3(a)]. This can be avoided by using a PFN with matched termination.

A high-discharge current in vacuum (vacuum spark) produces a great amount of plasma. Although the dense plasma expands during its flight from the electrode region to the extractor grid system, its density at the grid was found to

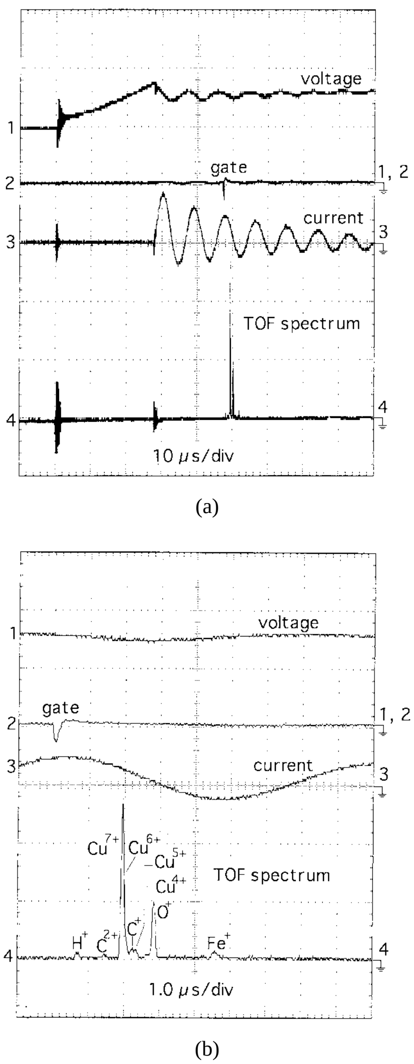

Fig. 3. (a) Overview of a single discharge with copper electrodes in vacuum. 1: extractor voltage (10 kV/div). 2: TOF gate potential (10 kV/div). 3: discharge current (5 kA/div). 4: TOF signal (20 mV/div at 50-Ω termination). The channel numbers 1–4 are shown on the left side for each curve, while the numbers on the right side show the position of the ground potential for each channel. (b) Same discharge as shown in (a), but with higher time resolution revealing the details of the TOF spectrum which is discussed in the text. The higher time resolution was obtained using the zoom function of the digital storage oscilloscope TDS 744.

be too high for optimum extraction. One way of overcoming this problem is to increase the distance between the discharge electrodes (location of plasma production) and the extractor grids (location of ion extraction). A greater distance allows further plasma expansion until optimum extraction at the grid (perveance match condition) can be reached. It is educational to do the following order-of-magnitude estimate. Let us assume that the plasma expansion law for low-current vacuum arcs [7]

$$n \approx \frac{\gamma I}{r^2} \tag{3}$$

can be extrapolated to high currents [n is the plasma density $(\mathrm{m}^{-3}), \gamma \approx 10^{13}\ \mathrm{A}^{-1} \cdot \mathrm{m}^{-1}, I$ is the discharge current (A), and r is the distance from the cathode spot (m)]. It is known that optimum extraction for vacuum arc ion sources is typically obtained at about $n \approx 10^{17}\ \mathrm{m}^{-3}$ ($I = 100$ A and $r \approx 0.1$ m); see [8], [9]. Optimum extraction for a vacuum spark ion source is reached at $r \approx \sqrt{\gamma I/n} \approx 1$ m for $I = 10$ kA. (At this very large distance, all cathode spots appear as one plasma emission center; thus, (3) can be used for the purpose of this estimate.) The diameter of the ion beam should be of the same order of magnitude (i.e., 1 m) to utilize a reasonable fraction of the amount of plasma available. A vacuum spark ion source is therefore inherently a very broad beam ion source. Going to smaller distances and diameters implies not only less efficient utilization of the plasma, but creates breakdown problems at the extractor and makes extraction impossible: the dense plasma "flows" through the beamlet holes of the extractor and shorts them. Since we are interested only in proof-of-principle experiments, we have artificially reduced the plasma density by inserting two stainless steel meshes in the expansion zone between the electrodes and the extractor (total transparency about 0.1). An additional useful "trick" is to place a fine metal mesh onto the first extractor grid, thus defining and stabilizing the plasma boundary [10]. This is particularly useful because the plasma density at the extractor is not constant in our experiment.

A typical result of our proof-of-principle experiments with copper electrodes is shown in Fig. 3(a) and (b). Channel 1 shows the potential measured at the electrode which is connected to the first (plasma facing) extractor grid (=extractor voltage). The noise at the first division indicates the breakdown of the spark gaps of the Marx generator and the beginning of the charging of the final capacitor. The potential increases until the vacuum spark gap breaks down. This is the beginning of the oscillating discharge current. The TOF gate is set to investigate the plasma composition at a given time [the maximum of the fifth half-cycle in the example of Fig. 3(a) and (b)]. Fig. 3(b) shows that the first ions arrive 600 ns after the gate pulse at the TOF detector, which is a magnetically shielded Faraday cup, located 1.1 m downstream from the gating plates. These first ions are hydrogen; they originate together with oxygen and carbon from the Lucite window which was placed, at the time of these investigations, close to the vacuum discharge gap. The slowest ions are iron ions which came from the plasma attenuator (SS meshes). Stainless steel contains mainly Fe (about 68%), Cr (about 19%), and nickel (about 10%). The Fe^{+} line is likely to be slightly broadened by these other elements of similar mass. The lines of Cu^{7+} and Cu^{6+} are merged because they could not be resolved with the TOF spectrometer used. The maximum of the observed line is located where the Cu^{7+} ions are to be expected, and the Cu^{6+} ions cause an asymmetric shape of the line.

The charging voltage in the example of Fig. 3 was 10 kV and the extractor voltage was 16 kV at the time of extraction of the ions under investigation. Since the highest ion charge state of copper was 7+, the energy of these ions was 112 kV.

The maximum total ion beam current was about 100 A, measured by a large beamstop 0.5 m downstream of the extractor. This corresponds to a current density of about 100 mA/cm^2. However, as previously mentioned, the present system was not designed for optimum plasma utilization, but as a proof-of principle experiment for the use of a modified Marx-generator and high-charge state generation.

IV. Outlook

It has been shown that a pulsed ion source can be operated with a single power supply combined with a Marx-generator-like circuit; no floating power supplies are required. The principle can be applied to various pulsed ion sources, but is particularly suited to an ion source utilizing vacuum sparks for plasma production. The number of Marx stages used for the extractor voltage versus the number used for plasma production can be adapted to the specific kind of source and energy range desired. The voltage can be scaled up to obtain ion beams of megaelectronvolt energy using voltages smaller than 100 kV. Experiments with external pulsed magnetic fields indicate that the ion charge states can be further enhanced [10], [11]. Problems such as shot-to-shot reproducibility, electrode erosion and replacement, enhanced duty factor (pulse repetition rate) and related power and cooling problems, and long-term stability have to be addressed in the future.

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