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Abstract

Ion energy of the beam formed by an ion source is proportional to extractor voltage and ion charge state. Increasing the voltage is difficult and costly for extraction voltage over 100 kV. Here we explore the possibility of increasing the charge states of metal ions to facilitate high-energy, broad beam ion implantation at a moderate voltage level. Strategies to enhance the ion charge state include operating in the regimes of high-current vacuum sparks and short pulses. Using a time-of-flight technique we have measured charge states as high as 7+ (73 kA vacuum spark discharge) and 4+ (14 kA short pulse arc discharge), both for copper, with the mean ion charge states about 6.0 and 2.5, respectively. Pulsed discharges can conveniently be driven by a modified Marx generator, allowing operation of "Magis" with a single power supply (at ground potential) for both plasma production and ion extraction.

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1. Introduction

High energy metal ion implantation is usually done either with a low current, charge-to-mass analyzed beam of small cross section or with a broad beam of multiply charged ion produced by a Mevva-type ion source. The ion energy is given by

$$E_i = Q_i \, e \, U_{extr} \tag{1}$$

where Q_i is the ion charge state, e is the elementary charge and U_{extr} is the extractor voltage. For high energy ion implantation one has the option to increase the extractor voltage or the ion charge states, or both. Increasing the voltage is straight forward but causes technical difficulties as well as high costs when approaching the region of hundreds of kilovolt. Therefore, it is desirable to explore feasible, cost-effective ways of producing plasmas containing highly charged ions and extracting usable beams. In this paper we report about the concept of a novel, broad-beam, **Ma**rx-generator-based **i**on **s**ource "Magis" which is designed to produce metal ion beams whose energy is high primarily due to high ion charge states. Various regimes of operation have been tested, and we report about the achievements as well the problems we have encountered.

2. Starting point: Mevva ion sources, their features and limitations

In Mevva (**Me**tal **v**apor **v**acuum **a**rc) ion sources, ions are extracted from the metal plasma produced at cathode spots at relatively low arc currents of order 100 A. The ion charge states are typically in the range 1-4, depending on the material. A table of ion charge state distributions (CSDs) is given in the review paper by Brown [1]. The formation of ions at cathode spots can be explained taking into account that the dense spot plasma becomes a non-equilibrium plasma with a "frozen" ion CSD when expanding into the vacuum. CSDs have been calculated for all conductive elements of the Periodic Table [2]. It was found that the CSD of each element depends strongly on the temperature of the dense cathode spot plasma. Typically, the temperature is 1.8 - 3.6 eV, depending on the element, in the transition region from equilibrium to non-equilibrium. The plasma temperature is a result of energy balance of the cathode spot. The energy input during an arbitrary time interval, τ, is given by

$$E_{in} / \tau = U_{arc} \, I_{arc} \tag{2}$$

and distributed to various forms of energy such as ionization energy, enthalpy of atoms, ions and electrons, heating of the cathode, etc. (an example of an energy flux diagram is given in [1]). The arc voltage (U_{arc} = potential difference between anode and cathode) is about 20 Volts for all metals at arc currents, I_{arc}, of order 100 A in the absence of an external magnetic field, and therefore there is roughly the same energy input for all cathode materials.

Experimentally it was found that there is a correlation between the boiling point of the cathode material and the mean ion charge [1]. This correlation on the one hand and the constant energy input on the other hand suggest that the energy input per plasma amount is a better parameter than the energy input itself. It also offers an alternative explanation why the mean ion charge state is enhanced at the beginning of each Mevva pulse: the amount of plasma, in which the energy is invested, is small at the beginning of each pulse. An increase in arc current increases proportionally the amount of plasma, and only little change in the CSD can be expected. This has been confirmed for the range 20-180 A [3]. Therefore, based on the vacuum arc plasma physics, Mevva ion sources have their characteristic, element-specific CSDs, and there is not much one can do to change the CSDs unless the discharge conditions are drastically changed.

3. Possible strategies for increasing ion charge states of vacuum arc plasmas

3. 1. Application of a magnetic field

It is known that the arc voltage increases in the presence of a transverse magnetic field, and, at constant current and plasma production, an increase in energy input per plasma amount can be expected. The enhanced energy input is followed by a higher plasma temperature leading to higher charge states. Indeed, this effect has been observed [3, 4], with a typical enhancement factor of 1.3 - 1.5. A related effect was observed when the arc current reached the kA region [5] which can be attributed to the self-magnetic field.

3. 2. Operation at very short pulse lengths

It is known that higher ion charge states can be observed at the beginning of each arc pulse (see, e.g., [6, 7]. This suggests operating with very short pulses, i.e. to terminating each discharge pulse before the mean ion charge reaches its low value. Of course, an implantation facility must operate at a high pulse repetition rate to achieve an overall acceptable duty cycle.

3.3 Operation in the high-current, vacuum-spark regime

The current of a vacuum arc is usually limited by the ohmic and inductive resistance of the electric circuit. If the ohmic resistance and inductive impedance are made as small as possible, the discharge current is largely determined by the plasma impedance, allowing very high currents. This is the regime of "vacuum sparks". Extremely high charge states such as H-like and He-like Ti and Fe have been spectroscopically observed in "hot spots" (see, for instance, [8-11] These hot spots are micron-size regions of plasma instabilities with a lifetime in the sub-nanosecond range. Although it is not possible to extract these extremely highly charged ions to form an ion beam, it is challenging to see whether ions can be extracted whose charge states are significantly higher than those obtained with Mevva ion sources.

4. "Magis" - a Marx-generator-based ion source for high-energy metal ion implantation

For Magis, all of the above strategies can be applied. However, strategy 3.1, the application of a magnetic field, results in only a modest ion charge state enhancement. Therefore we focus here on the other two strategies which make use of pulsed power. A Marx generator is a source of pulsed power for high voltage applications [12]. The basic idea is to charge N capacitors in parallel and switch them simultaneously in series so as to obtain N-times the charging voltage (losses neglected). Often spark gaps are used as switches. In our experiments, various modifications of this concept have been used to produce both the metal plasma and to boost the plasma potential to high positive values. In one version, some sections of a Marx generator were used to pulse-charge a high-voltage capacitor which severed as the supply for a high-current vacuum spark. The results of these experiments have been published recently [13] . Here we report on other versions of the technique.

Fig. 1 shows the electrical schematic and principal construction of Magis. An important feature is that only one power supply is used for plasma production and ion extraction. The negative side of the power supply is grounded, and no floating of any power supply is required which results in simplified construction, reduced costs, and safer handling. The extractor voltage can be increased by adding more Marx stages.

To explore strategy 3.3, the extraction of ions from a vacuum spark discharge, the final stage was a low-inductance, high-voltage capacitor (2.76 μF, max. 50 kV), that was connected to the coaxial electrode arrangement. The total circuit inductance was about 150 nH. The electrode spacing was small (less than 0.5 mm) so that the vacuum gap broke down earlier than the Marx spark gaps. After breakdown, the plasma potential was between ground and the charging potential U_0. Consequently, the potential at point "A" (Fig. 1) shifted to a negative value which caused the last Marx spark gap to break down. This, in turn, triggered the remaining Marx spark gaps. Each section of the Marx generator shifted the plasma potential positively by U_0. We have easily obtained an extractor voltage in excess of 100 kV for a charging voltage of only $U_0 = 15\,\mathrm{kV}$. An advantage of this scheme is that the high discharge current flows exclusively through the vacuum gap, not through a Marx gap as proposed in [14]. Figure 2 shows the discharge current in vacuum, measured with a calibrated Rogovsky coil, and a time-of-flight (TOF) charge-to-mass spectrum. The electrode material was copper, and the vacuum base pressure in the 10^{-6} Torr ($\approx 10^{-4}$ Pa) region. The maximum current was 73 kA at a charging voltage of 17 kV. The first plasma arrived at the extractor grids (located 0.5 m from the electrodes) after 3 μs but the maximum plasma density was observed 10 μs after the beginning of the discharge. This indicated that the plasma is faster (higher energy) than vacuum arc plasma (for which typically $v_{pl} \approx 1-2\times10^4\ \mathrm{m/s}$). The TOF spectrum shows clearly that the CSD is significantly shifted compared to a Mevva-CSD of copper whose mean charge state is about 2.0. Most ions have a charge state 5+ or 6+, and even higher charge states are present (not resolved). The mean ion charge state of the beam shown in Fig. 2 is about 6.0, resulting in a mean beam energy of 102 keV.

From the point of view of charge states and resulting ion energy, the use of vacuum spark discharges could be scaled up to higher currents and voltages. However, with each discharge, about 0.5 Coulomb is transferred. Taking into account that the electrode erosion rate is of order 100 μg/C one can estimate that not more than 100 discharges can be made without having to adjust the electrode spacing. This was done manually and can be improved by either having an automatic electrode feed motion or using another electrode arrangement, for instance a surface discharge.

Less charge is transferred in the alternative approach, utilizing short discharges as described in strategy 3.2. This was tested by replacing the large 2.76 μF capacitor by a 1 Ohm pulse line. We used a 1 Ω cable pulse generator with a maximum voltage of 30 kV. The current pulse was rectangular with a duration of 440 ns when a matching 1 Ω low-inductance resistor was used, and oscillated for 8 μs when driven without this resistor. The arrival time of the plasma at the extractor grids and the discharge voltage indicated that the plasma made by the cable discharge is arc-like. TOF spectra, like the one in Fig. 3, show that enhanced charge states exist (3+ and 4+ for copper) but the majority of ions have the charge state 2+. Obviously, the energy density and plasma temperature are not greatly enhanced compared to long-pulse, low-current vacuum arcs.

Based on the previous experiments we decided to utilize a low-inductance, high-current discharge with relatively small charge per discharge. This was accomplished using a low-inductance, high-voltage capacitor of 0.29 μF. TOF measurements show that the CSD is dominated by the charge states 4+ and 5+.

The electrical scheme can be optionally simplified by removing all Marx-stages left of point "A" (Fig. 1). The potential of "A" is then always ground, and the plasma potential (= extractor voltage) is the charging voltage of the capacitors at breakdown. Because all Marx spark gaps are omitted, this scheme had the best reliability and appeared to be an elegant solution for the case when a relatively low extractor voltage is acceptable.

Test implantation of copper in silicon have been done with the breakdown voltage in the range 8-12 kV. The implantation depths profile was investigated by Rutherford backscattering and showed a broad concentration peak at a depth of 350 Å. The peak concentration corresponds to a mean copper ion energy of 41 keV according to TRIM calculations. A mean ion charge state of 4.1 can be deduced assuming an average extraction voltage of 10 kV; this is in agreement with TOF measurements. The high-energy tail of the profile ranges up to a depth of 880 Å (corresponding to 120 keV). That is much deeper than the calculated longitudinal straggling of 120 Å at 41 keV and can easily be explained by pulse-to-pulse variations of the extraction voltage, ion charge states, and longitudinal straggling at higher energy.

5. Conclusions

The Magis approach can in principle generate metal ion beams with energy up to hundreds of kilovolts using a single power supply of moderate voltage (tens of kilovolt). High ion energy is obtained utilizing highly charged ions and voltage multiplication. The highest ion charge states have been observed in the vacuum spark regime (low-inductance high-current capacitor discharge). It was found that the charge transferred per pulse should be kept small for practical implantation purposes.

Acknowledgments

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Figure Captions

Figure 1

Electrical scheme and principal construction of Magis.

Figure 2

Discharge current in vacuum (50 kA/div), top, and time-of-flight (TOF) spectrum, bottom, with TOF gate, center. The electrode material was copper, and the extraction voltage 17 kV.

Figure 3

CSD for a copper discharge in vacuum driven by a 1 Ohm cable pulse generator.

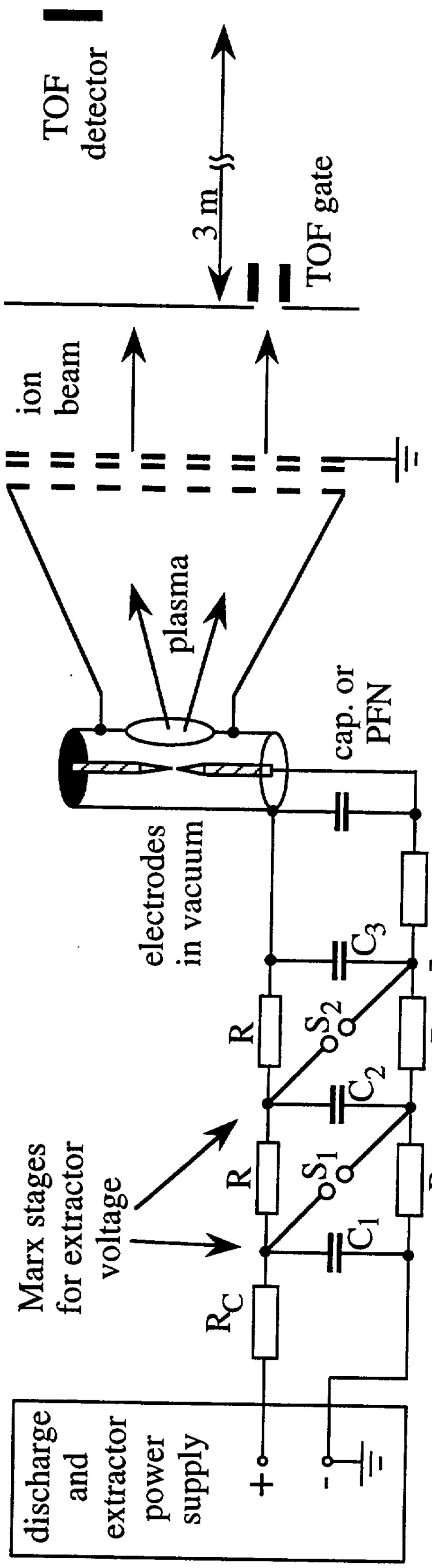
TOF detector
3 m
TOF gate
ion beam
plasma
cap. or PFN
electrodes in vacuum
R
C_3
A
R
S_2
R
C_2
S_1
R
R
C_1
R_C
Marx stages for extractor voltage
discharge and extractor power supply
+
-

Fig. 1

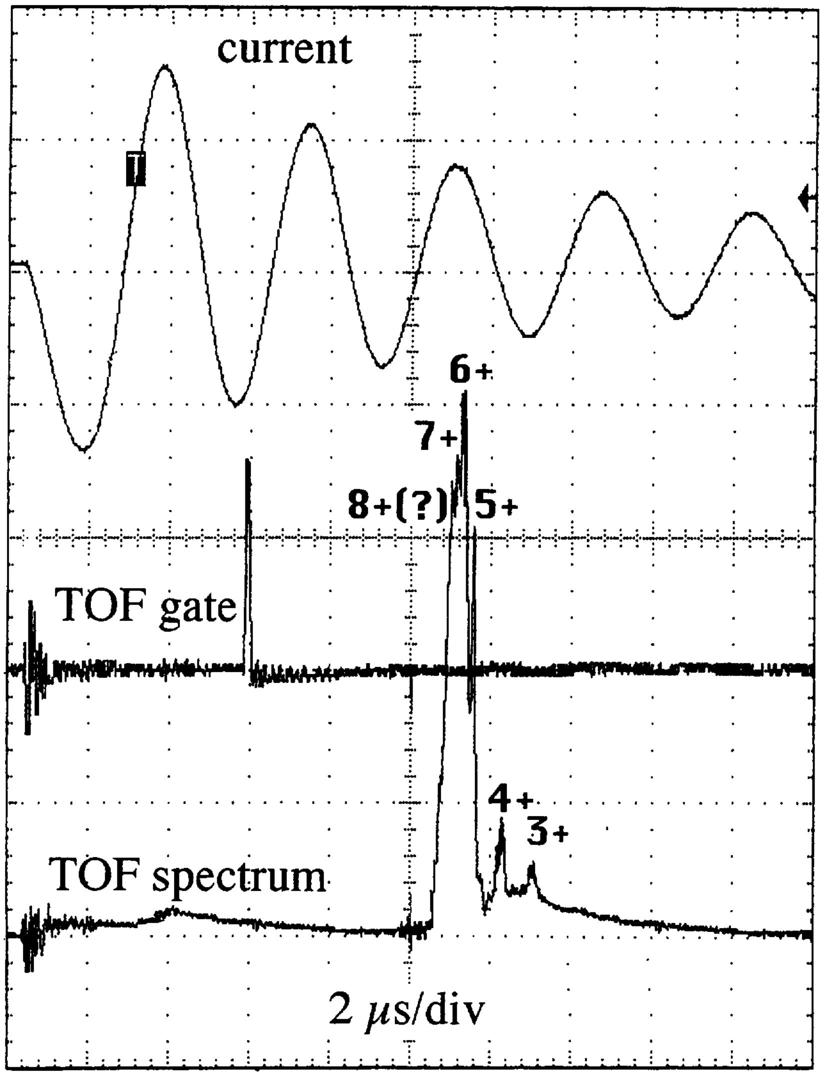

Fig. 2

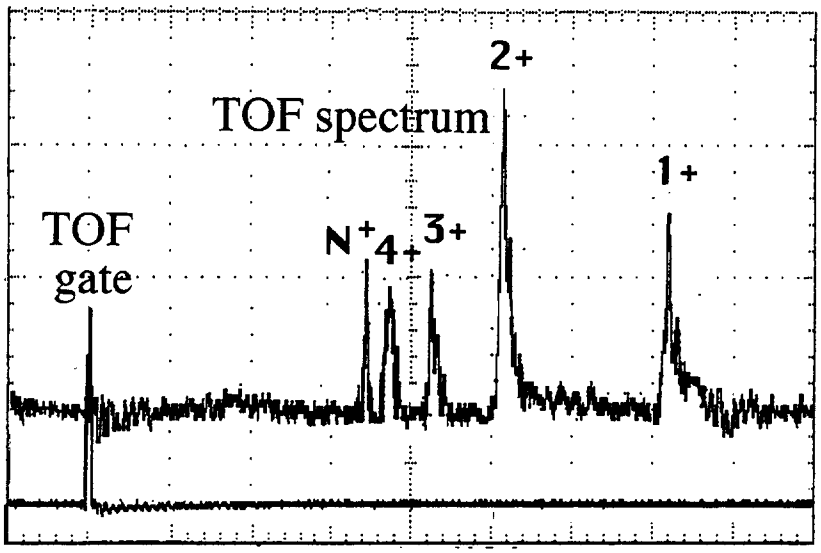

Fig. 3