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Recent developments and upgrades in ion source technology and ion beam systems at HVE

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ABSTRACT

In this paper we discuss various ion sources used in particle accelerator systems dedicated to ion beam analysis techniques. Key performance and characteristics of some ion sources are discussed: emittance, brightness, gas consumption, sample consumption efficiency, lifetime, etc. For negative ion sources, we focus on the performance of volume H^- ion sources (e.g. HVE model 358), the duoplasmatron negative ion source and the magnetically filtered multicusp volume sources (e.g. HVE model SO-120). The duoplasmatron ion source has been recently upgraded with a Ta filament to deliver up to 150 μA H^- ion beams and in conjunction with the Na charge exchange canal up to 20 μA of He^-. The available brightness from the duoplasmatron increased from 2 to 6 A m^{-2} rad^{-2} eV^{-1}. The ion source has been incorporated in a stand-alone light ion injector, well suited to deliver 20–30 keV negative ion beams of H^-, He^-, C^-, $NH_x{}^-$ and O^- to accelerate for most ion beam analysis techniques.

1. Introduction

Ion beams with energies of 1–4 MeV are commonly used in accelerator facilities to perform routine Ion Beam Analysis (IBA) of various samples, ranging from biological cells to cultural heritage and semiconductor devices [1–4]. Rutherford Backscattering Spectrometry (RBS), Particle Induced X-ray Emission (PIXE), Particle Induced Gamma-Ray Emission (PIGE), Nuclear Reaction Analysis (NRA), and Elastic Recoil Detection (ERD) are well-established techniques that provide quantitative information about structure and elemental composition of materials. The size of the ion beam on target can be reduced to 1 μm or below using high demagnification lenses, enabling techniques such as μ-PIXE which provide elemental maps of the samples with (sub)micron resolution [1]. Most common ion beam species required in the techniques mentioned above are ^{1}H, ^{4}He, ^{12}C, ^{15}N, ^{18}O and, in the case of ERD, heavier ions. Typical ion beam currents used in IBA are ranging from tens of *pA* up to hundreds of *nA*, for which the ion source is not a limiting factor. However, for microprobe applications an ion source that is able to deliver high ion beam brightness (typically >10 A m^{-2} rad^{-2} eV^{-1}) is essential. In this work we investigate the typical ion sources used in accelerators for IBA and we highlight their performance and key attributes. We also highlight the recent developments in ion source technology at High Voltage Engineering Europa (HVE) with focus on upgraded duoplasmatron (358) ion source, the Na charge exchange canal and a new stand-alone single source ion injector for production of negative light ions such as H^-, He^-, C^-, $NH_x{}^-$, and O^-.

2. Ion sources and ion beams – attributes and characteristics

Key attributes that characterize ion source performance include: ion beam emittance, ion beam brightness, plasma hash, energy spread, and gas/solid target consumption efficiency.

The ion beam emittance ε is defined as the area *S* of the two-dimensional phase space divided by π; $\varepsilon = S/\pi$ and also: $\varepsilon_x = x_0 \times x'_0$ and $\varepsilon_y = y_0 \times y'_0$, x_0 and y_0 are the beam radii in horizontal (*x*) and vertical (*y*) planes at a waist, while x'_0 and y'_0 are the beam half angle divergences in the *x* and the *y* planes. The energy-normalized emittance is obtained by multiplying the emittance ε with the square root of ion beam energy. Degradation of normalized beam emittance from the ion source to the target is a measure of the quality of the beam transport system.

The ion beam brightness (*B*) is defined as the ion beam (particle) current, *i*, that can be transported through two apertures of areas, A_o (object area) and A_c (collimator area), separated by a drift *L*, at a given ion beam energy (*E*): $B = \frac{i \times L^2}{A_0 \times A_c \times E}$. To allow comparison of the performance of the microprobes at various facilities, Szymansky and Jamieson defined the normal brightness [5] at a half-angle divergence of 0.07 *mrad* and at an object slit opening yielding

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the highest ion beam brightness. Clearly, high beam brightness is advantageous for microprobe applications.

The ion beam energy spread can negatively influence the optical properties of high quality lenses, i.e. nuclear microprobe lenses. For tandem accelerators, the ion beam energy spread ΔE is dependent on mainly three factors: the initial beam energy spread from the ion source, the energy spread introduced by the interaction with the stripper gas, and the terminal voltage ripple. The beam energy spread introduced by the ion source is dependent on many plasma parameters, which ultimately transfer kinetic energy to the ions. Ion sources with ion beam energy spread below 10 eV are considered good for IBA experiments. This value should be compared to the terminal voltage ripple for all-solid-state particle accelerators, typically in the range of 15–100 V_{RMS}.

3. Ion sources for different types of particle accelerators

Single-ended particle accelerators benefit from the use of direct positive extraction ion sources located in the high voltage terminal. Positive ion source are more prolific in producing high intensity ion beams. Only the ion source energy spread and the accelerator terminal voltage ripple determine the beam energy spread.

Typically, single-ended particle accelerators are preferred when highest brightness is required. State-of-the-art work in IBA with single-ended particle accelerators includes high-resolution microprobe work, with typical probe size down to 100 nm and below. The 3.5 MV Singletron™ accelerator systems installed at e.g. the National University of Singapore (NUS) [6] and at the Centre Etudes Nucléaires de Bordeaux, Gradignan [7] are specially designed for high brightness and high stability for microprobe applications. The most common ion source employed in single ended particle accelerators is the RF ion source. A ~100 MHz RF field is capacitively coupled to magnetically confined plasma. Such ion sources can produce ion beams of H, He, N, O, Ne, Ar, Kr, Xe. The ion beam energy spread is typically about 100 eV while the normalized emittance is $\sim 1.5\ \pi$ mm mrad $MeV^{1/2}$. To date, the highest ion beam brightness ($74\ A\ m^{-2}\ rad^{-2}\ eV^{-1}$) measured for microprobe applications, has been recorded at the Singletron™ at NUS, which is fed by the RF ion source HVE model 173. The gas consumption of the RF ion source for ^3He can be as low as 0.25 sccm. Maintenance cycle of an RF ion source is at approx. 1000 h.

Tandem accelerators require negative ion beams for the injection. In contrast to single-ended particle accelerators the ion sources are easily accessible and the injection configuration allows multiple ion sources to be applied with ease. Tandem accelerators have the advantage that the ion source maintenance can be done much faster than in single-ended particle accelerators. Negative ion sources for tandem injectors include gas sources: von Ardenne type, multicusp type or RF type and cesium sputter type ion sources.

Cesium sputter type ion sources use energetic Cs^+ beam of particles that strike a solid surface with target material. The sputtered atoms may pick up electrons due to a lowered work function introduced by the Cs layer at the surface of the target, thereby forming a negative beam. In such manner, negative ion beams (100's of nA to hundreds of µA, depending on species) from almost the entire periodic table can be created. He^- beams cannot be created in Cs sputter type ion sources. Negative H^- ion beam currents created from TiH target pieces can be prolific (e.g. ~100 µA HVE ion source model 860A, SO-110), intensities more than sufficient for IBA. Related to ion beam emittance the typical value for the emittance is 2–12 π mm mrad $MeV^{1/2}$. However, microprobe work is usually performed with gas type ion sources since the brightness is at least a factor of three higher. The lifetime of the sputter target is a drawback for this type of ion source. Additionally, the ion beam current output may vary with time.

RF ion sources (only positive ion extraction) coupled to charge exchange canals (vapors of Li, Na, Rb) can provide negative H, He, C, O ion beams for IBA. Charge exchange efficiency is typically a few percent, and the beam current is from several hundreds of nA's up to 10 µA. The beam energy spread (~100 eV) is large when compared to other direct negative extraction ion sources. The charge exchange process in the alkali vapor introduces additional energy spread. When discussing the alkali vapors used in the charge exchange canals, the work of Slachter et al. [8] indicates that the highest charge exchange efficiency for He is achieved for Na when the beam energy is 20 keV, energy well suited for beam transport and injection into Tandetron™ accelerators.

3.1. Gas discharge type ion sources

A series of ion sources can produce direct negative extraction of ion beams of e.g. H, C, NH_x, O. We will focus on the volume H^- ion sources, the magnetically filtered multicusp volume source [9–11] (e.g. HVE model SO-120) and the duoplasmatron negative ion source [12] (e.g. HVE model 358).

The HVE model SO-120 multicusp ion source has been developed to deliver 1–3 mA intensity H^- ion beams with direct negative extraction. Details of this ion source has been discussed in several previous papers [13,14], indicating high beam brightness ($30–40\ A\ m^{-2}\ rad^{-2}\ eV^{-1}$, value after ion beam extraction and mass analysis), the low beam energy spread (<5 eV), low hash (<1%) and the long filament lifetime (more than 500 h). High ion beam brightness and low beam energy spread delivered by the ion source have been key requirements for the IBA microprobe community, e.g. at the Jozef Stefan (JSI), Slovenia and the Technical University (TU) Munich, accelerator facilities. A sevenfold normal brightness increase (currently $14\ A\ m^{-2}\ rad^{-2}\ eV^{-1}$) at the microprobe lens position has been reported at JSI when compared to the previous duoplasmatron beam brightness. The brightness figure has been recorded when injecting only 20% of the beam current available from the SO-120 multicusp ion source [15]. Results from TU Munich indicate that the SO-120 ion source coupled to the 14 MV vdG tandem particle accelerator increased the brightness available at the SNAKE microprobe from $0.1\ A\ m^{-2}\ rad^{-2}\ eV^{-1}$ (from an electron cyclotron resonance ion source + CEC) to $0.8\ A\ m^{-2}\ rad^{-2}\ eV^{-1}$ [16]. The SO-120 multicusp ion source is housed in a small footprint ($1.8 \times 1.4\ m^2$) dual source multicusp injector and the constructive details have been previously given [13]. For negative He ion beam production, the combination between the direct positive extraction HVE model SO-130 multicusp ion source (~13 mA of He) and the Na CEC yields negative He ion beams currents in excess of 70 µA [14]. To conclude, the multicusp ion sources can yield high brightness & current hydrogen beams for tandem accelerators, brightness values that start to approach or even exceed beam brightness values typically reserved for single-ended particle accelerators.

The duoplasmatron ion source can operate with direct negative extraction for ion beams of H (in off-axis beam extraction mode) or is used for direct positive extraction for He ion beams. Traditionally, the filament is a PtIr mesh coated with an oxide layer (e.g. $BaSrCaCO_3$), for increased electron emission coefficient while operating at low filament temperature (~1000 K). Since the duoplasmatron can provide direct extraction of C^-, NH_x^-, and O^-, but these gases lower the lifetime of the PtIr gauze, HVE upgraded its duoplasmatron with a Ø1.3 mm Ta filament. The power supply package driving the duoplasmatron was upgraded to support operating the Ta filament. The filament support base has been modified to allow cooling of the filament feedthrough, while the filament shape and location have been optimized to facilitate stable plasma conditions. An XYZ manual stage was added to allow manual optimization of extraction geometry over a large current density range.