

## 科学研究費助成事業 研究成果報告書

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研究課題名(和文) X線レーザーを用いた量子光学研究のためのイオン・トラップ装置の開発

研究課題名(英文) Development of an ion trap apparatus for quantum optics experiments using an X-ray laser

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研究成果の概要(和文)：永久磁石を用いた電子線イオン・トラップを制作した。装置開発の目標として 1)超伝導磁石の利用に伴うコスト、設計の複雑さ、および検出器立体角の減少を避けるため永久磁石の利用、2)トラップ中心磁場 1.0 T 以上、3)蛍光検出のため最大限の立体角の確保、4)電子ビームのエネルギー5 keV、電流1 mA以上とした。

真空チェンバー、磁気ポールピース、磁気サーキット、それから電子銃と電子光学一式を制作した。現在使用可能の磁石32枚の内16枚の利用でトラップ中心磁場 0.8 Tに到達した。1 keV, 1 mAの電子線の利用が可能で、可視分光を用いてアルゴンイオンの生成を確認できた。

研究成果の概要(英文)：A permanent-magnet electron-beam ion trap apparatus optimised for use at a beamline has been designed and constructed. The design goals were i) to use permanent magnets, avoiding the cost, complexity, and loss of detection solid angle inherent to superconducting magnets, ii) a field strength in the trap of over 1 T, iii) a large field of view for fluorescence detection, and iv) initial electron beam parameters of 1 mA, 5 keV. The vacuum chamber, magnetic pole pieces, and other parts of the magnetic circuit were designed, constructed, and tested, along with an electron gun system. Presently, a field strength of 0.8 T has been reached using 16 out of a possible 32 magnets. An electron beam of current 1 mA and energy 1 keV has been successfully passed through the trap, and the production of argon ions demonstrated by detecting fluorescence at visible wavelengths.

研究分野：コヒーレントX線利用研究

科研費の分科・細目：物理系科学・原子・分子・量子エレクトロニクス

キーワード：量子光学

## 1. 研究開始当初の背景

Free-electron laser facilities are currently opening up new frontiers of research making use of unprecedented peak brightness, narrow pulse widths, and coherence properties at extreme ultraviolet (< 80 nm) and X-ray wavelengths. Techniques previously only available at microwave and visible wavelengths are expected to lead to new breakthroughs when extended to shorter wavelengths. At the 'SCSS' free-electron laser facility at SPring-8, steps had been made in this direction, with the highlight being the observation of superfluorescence in helium (*Phys. Rev. Lett.* **107**(19) 193603 (2011)). This required the high peak brightness and short pulse nature of the free-electron laser to achieve a high density of atoms in an excited state, which subsequently decay collectively and coherently. The observed emission was on a visible wavelength transition (502 nm). In order to observe similar effects at shorter wavelengths, it is necessary to find suitable level schemes, and rather than neutral atoms, medium to highly-charged ions offer exciting opportunities, albeit at lower densities.

In the early stages of this project experiments were continued at SCSS to further understand the superfluorescence decay schemes, and also to develop a gas-cell based monochromator (figure 1). Further details can be found in Harries et al. *J. Phys. B* 46(16) 164021 (2013), and *JPS Conf. Proc.* 1, 13083 (2014).

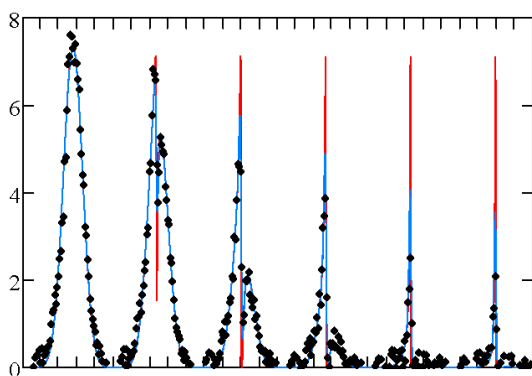


Figure 1 He\*\* gas-cell monochromator for SASE pulses at wavelengths near 20 nm. From left to right the six spectra correspond to increasing densities of helium in the gas cell, and show a progressively narrowing line width.

While the initial application envisaged the development of a linear quadrupole ion trap to be used at a beamline, it became apparent that the most suitable technology was an electron-beam ion trap (EBIT), which uses a tightly-focussed beam of electrons to create and trap highly-charged ions from a neutral target introduced at low densities. The EBIT offers more flexibility on the charge states which can be studied, and opens the door to many more fields of study.

## 2. 研究の目的

The study of highly-charged ions (atoms which have lost most of their electrons) provides information useful in fields as diverse as understanding spectra from X-ray space telescopes [Bernitt et al., *Nature* **492** p225, 2012], precision metrology and tests of QED, and ion therapy. A further application of particular interest is providing data for modelling plasma processes, for example the effect of tungsten wall impurities in the ITER plasma. Since electronic transitions in highly-charged ions extend from the visible into the hard X-ray wavelength range, synchrotron radiation and X-ray free-electron lasers are ideal tools for their spectroscopy. However due to the difficulty of creating high densities of particular charge states, it is only recently that such studies have come into their own [Rudolph et al., *Phys. Rev. Lett.* **111**, 103002, 2013].

Conventional EBITs are room-sized systems, which usually use liquid-helium cooled superconducting magnets to reach field strengths of up to 8 T. Such high field-strengths can compress high-current electron beams to extremely high charge densities, resulting in strong trapping of high charge states. However the magnet design leads to small angles of view of the trap region, running costs are high, and it is a large undertaking to transport the system to a beamline. This project aimed at constructing a table-top sized device using permanent magnets and with a large field-of view.

## 4. 研究成果

### 1. Construction of a compact EBIT

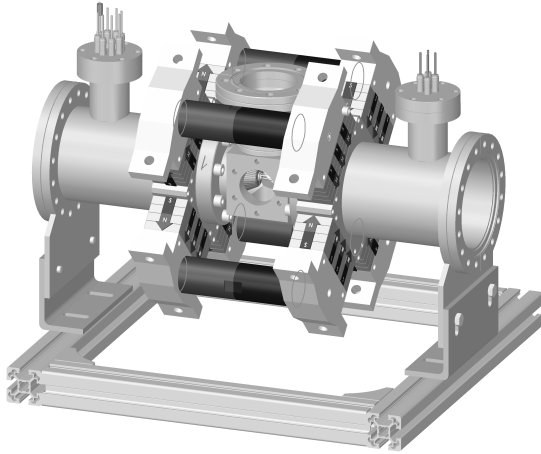


Figure 2 Overview of the apparatus constructed during this project. 4x2x4 magnets, 100 mm x 40 mm x 10 mm are used to create an axial magnetic field of strength up to 1.0 T.

Figure 2 shows an overview of the compact EBIT. At the centre is a stainless steel ICF70 cube with two ICF114 flanges. These connect to magnetic steel pole piece flanges, to which magnets are attached. Permendur steel pole pieces extend inside the cube to focus the magnetic field to the trap centre. Jigs (not shown) were constructed to safely mount and remove the strong magnets, and a turbo-molecular pump (not shown) provides a high vacuum. More details are provided below.

**Magnetic circuit.** The magnetic field was designed by performing simulations using the free 2-dimensional finite-element modelling software 'FEMM, using magnetic 'shells' rotated through 360° to approximate the magnets, caps, and rods. Figure 3 shows the simulated field strength, as compared to measurements made with a Hall-effect probe. Field strength can be adjusted by changing the number of the 10-mm-thick magnets used. Figure 2 shows 2 sets of 4 layers of magnets on each of 4 arms of the trap. The magnets can be removed without breaking vacuum, allowing online coarse adjustment of field strength, and also baking of the vacuum system (the grade N35 magnets have a maximum temperature of 80 °C). A stack of 4 magnets will provide field strengths greater than 1.0 T.

**Electron optics.** At the heart of the EBIT is an electron gun and collector system, which provides a high-current

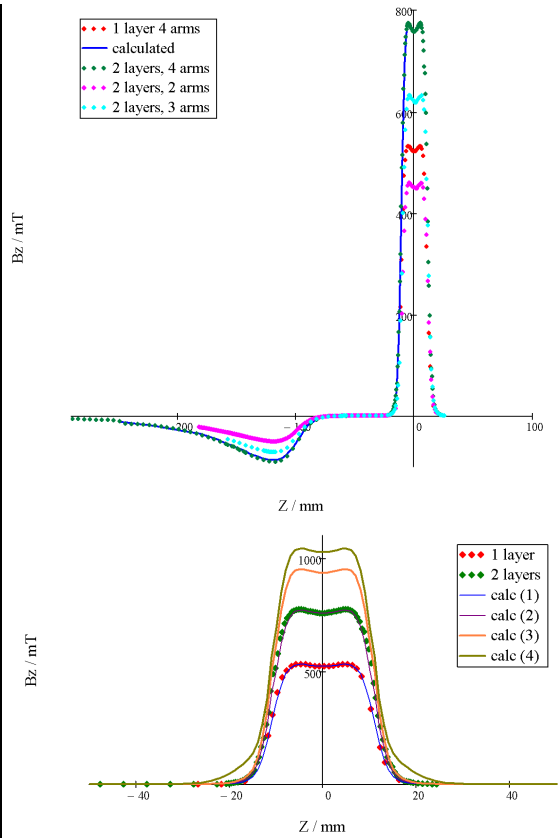


Figure 3 Measured and calculated magnetic field strength in the central trap region. Upper: The field is largest within the 22 mm gap between the two pole pieces, and is effectively shielded by the pole pieces in the region  $20 \text{ mm} < |z| < 100 \text{ mm}$ . The discrepancy between calculated and measured field is mostly due to the finite size of the Hall probe. The lower graph shows the field within the trap.

electron beam which is compressed by the magnetic field and is used to create and trap ions. To maximize the field strength in the trap region, the inner dimensions of the pole pieces are tight, making electron optics design critical. For the new EBIT a commercially-produced Ta cathode assembly is mounted in custom-designed electron optics. The collector assembly sinks the current passed through the trap. Preliminary tests have shown successful operation at electron energies up to 3 keV, and currents of greater than 1 mA have been observed on the collector. Work will progress to reach the limit of the current cathode, which is around 2 mA. The design allows for the future upgrade to a LaB<sub>6</sub> emitter, which could provide currents of up tens of mA.

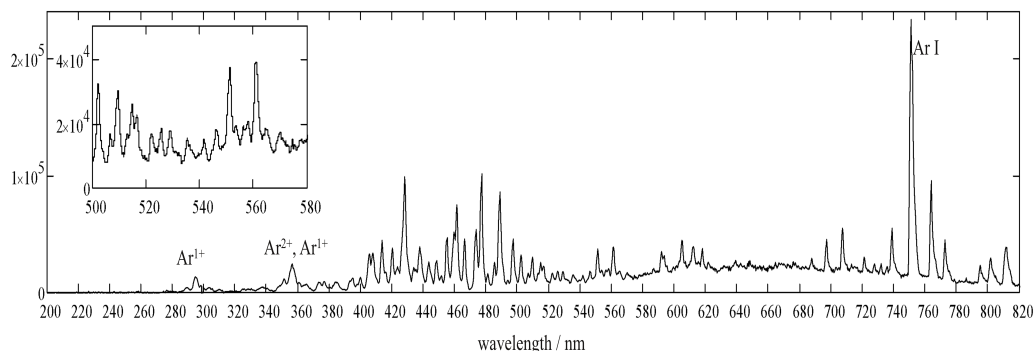


Figure 4 Spectrum showing visible-wavelength transitions in argon ions generated in the EBIT using an electron beam of energy 800 eV and current  $\sim 1$  mA.

**Preliminary results.** A fibre-optic visible wavelength spectrometer was used to verify the creation of ions. Figure 4 shows a spectrum recorded upon leaking argon gas into the trap, using an electron beam of energy around 800 eV and current around 1 mA. Most of the lines can be identified as being due to transitions in  $\text{Ar}^+$ ,  $\text{Ar}^{2+}$ , and  $\text{Ar}^{3+}$ , however evidence has also been obtained for the creation of  $\text{Ar}^{9+}$ , demonstrating that ions are being trapped and successively ionized. Imminent improvements to the electron beam, field strength, and vacuum are expected to lead to more efficient creation and trapping of highly-charged ions.

#### 5. 主な発表論文等

(研究代表者、研究分担者及び連携研究者には下線)

[雑誌論文](計2件)

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#### 6. 研究組織

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