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Ion Traps for Nuclear Decay Studies: a design for a handheld Electron Beam Ion Trap (EBIT)

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Abstract Nuclear decay studies of ionized species are of paramount importance in many astrophysical scenarios: from Big-Bang Nucleosynthesis to Cosmochronometers. Recently, new facilities, able to investigate nuclear decay in hot plasma, have been conceived and their design is in progress. Anyhow, the use of hot plasma in *ECR* traps intrinsically exhibits limitation due the high level of background and, on the other side, the necessity to push at the limit the *ECR* technology to get large plasma density and temperature. Here we report about a different approach, involving the design of an ultra-compact Electron Beam Ion Trap (μ -EBIT) able to perform nuclear decay studies for high charge-state ions confined in cold plasma. A preliminary design of the trap, assembly and magnetic field characterization is presented.

Keywords Astrophysics, Plasma Physics, EBIT, Nuclear Decay

INTRODUCTION

According to the actual knowledge of our Universe, 99% of the visible matter is made up of plasma, the so-called “fourth state of matter”. In the recent decades more and more efforts have been devoted to the investigation of such a wild environment with the aim of understanding in-plasma atomic and nuclear phenomena for applications in Nuclear Fusion reactors [1] and in Nuclear Astrophysics (decay rate measurements, exotic nuclear decay, Big-Bang Nucleosynthesis (BBN), Stellar Nucleosynthesis (SN) and, cosmochronometers [2-6]). In fact, in-plasma decay of radioactive species opens to a completely new and challenging field of investigation, since confining a hot plasma embedding High Charge-State Radioactive Ions (HCSRI) with a suitable density is not an easy task. According to the actual state of the art, two experimental approaches for studying nuclear decay of HCSRI are possible:

- Producing and accumulating radioactive species in storage-rings for in-flight decay measurements.
- Confining hot/cold radioactive plasma by magnetic/electrostatic devices.

The two approaches complement each other. In the case of storage rings the Gesellschaft für Schwerionenforschung (GSI) laboratory in Darmstadt (Germany) has established a reference in this field. At GSI a facility combining the heavy-ion synchrotron SIS [7], the in-flight fragment separator FRS [8], and the ion storage-cooler ring ESR [9] (see Fig. 1) has been operating for three decades, providing specific experimental conditions for decay studies of bare and few-electron exotic nuclei in ultrahigh vacuum. Consequently, it has been possible to produce, select, and store radioactive species with masses up to uranium with a defined number of bound electrons. Scientific achievements in the ESR storage ring range from cutting-edge measurements on cosmochronometers [4] to Electron-Capture (EC) decay-rate measurements on several ionized species [5]. In the latter case, EC decay-rate measurements of bare, H-like and He-like species assume paramount importance in the case of

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light species involved in BBN and SN. For instance, ${}^7\text{Be}$ plays a key role in Primordial Nucleosynthesis, directly involved in the so-called Cosmological Lithium Problem [2,10], and in the p-p II and p-p III branches in SN, determining the two monoenergetic solar neutrino lines as found in the calculated neutrino flux emitted by our Sun [11] reported in Fig. 2.

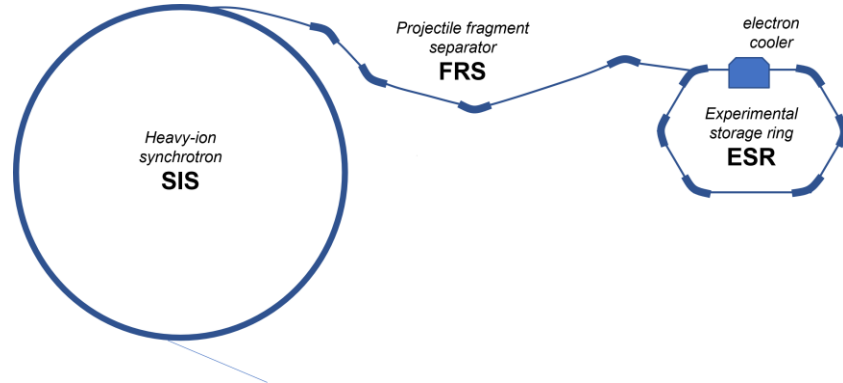


Figure 1. The FRS-ESR facility operating at GSI-Darmstadt: the SIS synchrotron accelerates heavy ions at relativistic energies towards a production target. Secondary ionized radioactive species are selected by the FRS and injected in the ESR, for in-flight decay-rate and mass measurements [9].

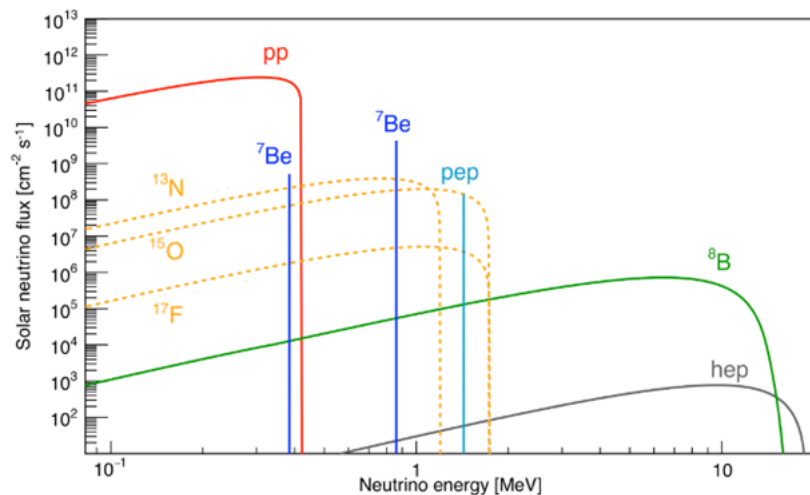


Figure 2. Solar neutrino flux as reported in ref. [11]: ionized ${}^7\text{Be}$ EC decay-rate in-plasma contribution can be found in the two blue monoenergetic lines and, consequently, by the p-p III branch to the neutrino high energy yield associated to ${}^8\text{B}$ β -decay.

On the other hand, measuring the decay rates of ionized species directly in hot/cold plasma allows to deduce the decay probability in a real and well characterized plasma environment. Even if the laboratory plasma regime can be different in terms of temperature and density with respect to the astrophysical environment as found in the solar core (conventionally described by the Debye-Hückel approximation) or in the first minutes of BBN, the interplay between nuclear and Coulomb interactions in a cloud of ions and electrons can be studied for the first time in a quasi-thermal condition. According to this approach, we first proposed a hot-plasma system based on the Electron Cyclotron Resonance ECR technology [12]. A high-performance ECR plasma-trap makes it possible to establish a well-controlled regime for temperature, ion charge-state distribution and plasma density, thus enabling the study of a specific nuclear decay-rate by using the hot quasi-stationary regime obtained inside the trap. Inherently the ECR approach is constrained by several limits: 1) the maximum charge-state achievable by the ECR heating/ionizing mechanism, if working in a quasi-thermal equilibrium; 2) the intrinsic electromagnetic background due to the very large flux of γ and X

rays coming from the hot-plasma fireball, seriously affecting the ancillary detection setup 3) the background coming from the decay of neutral species implanted or deposited in different parts of the trap 4) the limited space to arrange the detection setup around the confined plasma due to the presence of the devices producing the magnetic confinement (solenoid and multipoles). A way to overcome these issues is to use a cold-plasma system, as described in the next chapter.

NUCLEAR-DECAY STUDIES IN COLD-PLASMA TRAPS

The intrinsic limitation for decay-rate measurements in ECR hot-plasma traps can be partly overcome by considering the confinement of cold plasma, the main tradeoff emerging is due to the local plasma density, usually much lower in cold traps. With respect to this latter approach several configurations for ion trapping have been used, such as Paul Traps [13] and Penning Traps [14], sometimes associated also with laser cooling [15]. Most of them are extensively used as components of a mass spectrometer and for determining the nuclear magnetic moment of ionized species, but also in cutting-edge applications involving quantum computation and quantum information processing [16]. The working principle of a Penning trap involves periodic motion of the ions combining the cyclotron frequency to magnetron frequency, intrinsically related to the charge-to-mass ratio of the trapped ions (Fourier-transform ion cyclotron resonance mass spectrometry). A very effective evolution of such a concept, ISOLTRAP [17], was installed at CERN-Switzerland and it has been operating for three decades performing high-precision mass spectrometry of radioactive species produced by the ISOLDE-CERN facility [18].

To reach a high charge state in a confined cold ion-cloud a special class of traps, specifically conceived for this purpose, can be used: the Electron Beam Ion Trap (EBIT) [19]. These are the most compact devices for creating and studying highly charged ions as those involved in solar and explosive nucleosynthesis.

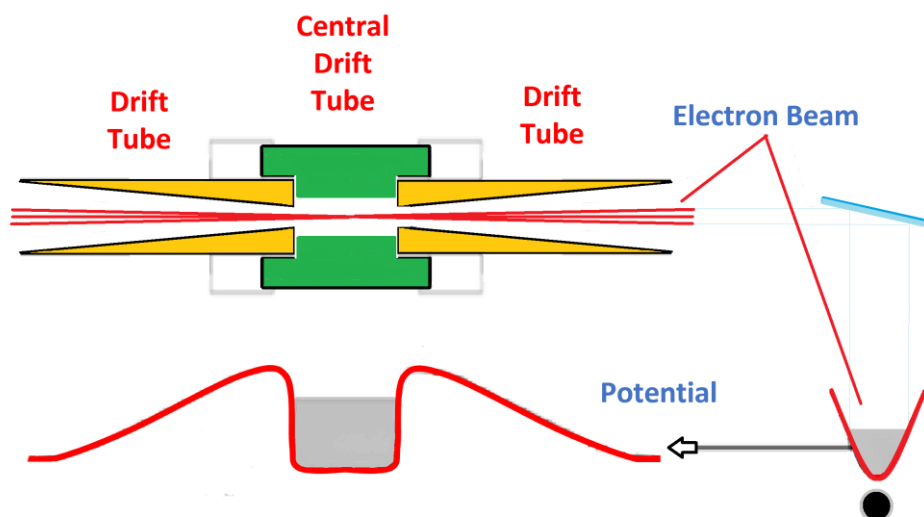


Figure 3. The EBIT scheme [19]. An axial compressed pencil-like electron beam sequentially ionizes the residual gas in the central part of the device (central drift tube). Axial and radial confinement is performed by the combination of a properly shaped axial electrostatic potential and the space charge effect of the compressed electron beam at the trap center.

As shown in Fig. 3 the EBIT implements a magnetically compressed electron beam to sequentially ionize atoms or ions. The high intensity e -beam, due to the compression, travels with very large current density in the trapping region, up to 5000 A/cm^2 , as in the Lawrence Livermore National

Laboratory (LLNL) EBIT trap [20], consequently the large charge-space density allows to achieve the long confinement time necessary for the multi-step ionization. In summary, for what concerns plasma confinement, radial trapping is achieved by the space charge of the electron beam, while axial trapping is performed by the negative biasing of a central drift electrode with respect to two external drift pipes. Ionization/recombination occurs by stepwise e-beam/ion collisions as depicted in Fig. 4.

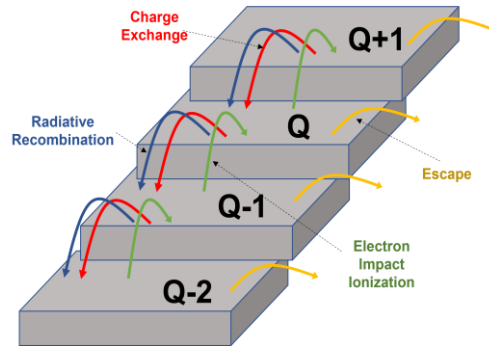


Figure 4. Multistep ionization mechanism occurring in an EBIT trap. Concurring processes as Radiative Recombination and Charge-Exchange must be taken into account to determine the final charge state distribution at the equilibrium and the confinement time. Electron beam current density and energy play a crucial role in maximizing both ion density and charge state in the trapping region.

It is worth noting that the description of the EBIT ion trapping can be made, at the equilibrium, in terms of the electrostatic potential of the system alone, simplifying a lot the simulations, since the *e*-beam optimization can be preliminary achieved by neglecting the presence of the low-density ion cloud. Consequently, the trapped plasma is “cold”, achieving an almost perfect thermodynamic decoupling between the *e*-beam (only responsible for the impact ionization) and the ion motion. In contrast to the ECR heating/ionization mechanism where a complete decoupling between fast-moving electrons and ions is much more difficult to achieve, also due to the broad energy distribution of the electrons scattered in the whole plasma volume (and on the internal wall of the device).

To optimize radial confinement in an EBIT, both large *e*-beam current and energy must be considered, in fact according to a first approximation (zero-electron-temperature) the compressed *e*-beam radius r_b can be obtained by the simple formula:

$$r_b (\times 10^{-6} \text{ m}) = \frac{150}{B(\text{Tesla})} \sqrt{\frac{I_e(\text{Ampere})}{\sqrt{E_e(\text{keV})}}} \quad (1)$$

where I_e is the electron beam current, E_e the *e*-beam energy and B the maximum magnetic field produced in the center of the trap. As already stated, one of the first and more performing EBIT was installed at Lawrence Livermore National Laboratory (LLNL) [20], it has been operating since the 90s establishing a benchmark for such a device, since the LLNL Super-EBIT can produce and confine most of the high-*Z* elements, up to bare uranium (U^{92+}). In the last decades many compact, still very effective, EBIT systems have been installed worldwide, it is worth mentioning the Heidelberg-EBIT [21], exploiting a unique permanent magnet configuration for *e*-beam compression and the compact SH-EBIT [22], operating by using permanent magnets in the energy range of 60–5000 eV, with a current density of up to 100 A/cm². Nowadays the technology to implement a high-performance EBIT is mature for opening the design and setup of these devices to the market; a noteworthy example is the DRESDEN EBIS-A [23] shown in Fig. 5, delivering top of the class performance, achieving *e*-beam current of 200 mA with an ionization factor exceeding 10²² e/cm².

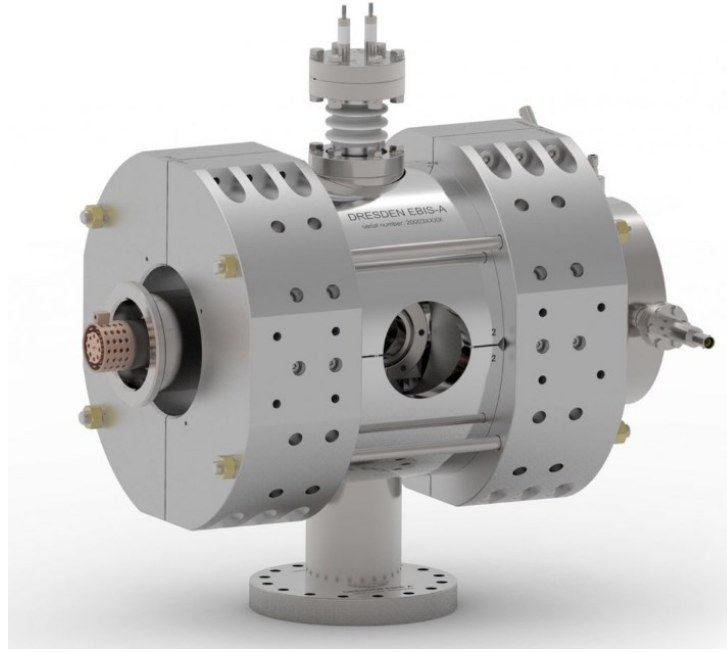


Figure 5. The DRESDEN EBIS-A [23], a table-top EBI Trap-Source implementing bakeable Nd-Fe-B permanent magnets for e -beam compression (photo by DREEBIT GmbH).

μ -EBIT DESIGN, PRELIMINARY SETUP AND SIMULATIONS

Considering the simple design scheme of an Electron Beam Ion-Trap and taking as a reference the many implementations of the device already in operation, we started at INFN-Catania the design and \mathbf{B} -field simulation of an ultra-compact EBIT built around specifically shaped Nd-Fe-B permanent magnets. The first step in defining the EBIT design was devoted to establishing a proper \mathbf{B} -field gradient along the trap axis to achieve the required e -beam compression: the preliminary geometry adopted is shown in Fig. 6. The cylindrical symmetry is sustained by a combination Nd-Fe-B magnets: two ring shaped elements (orange) coupled to 12 square prisms (red), constraining the \mathbf{B} -field circuit. Six square bars in combination with two nut-shaped soft iron elements (green) close the magnetic circuit.

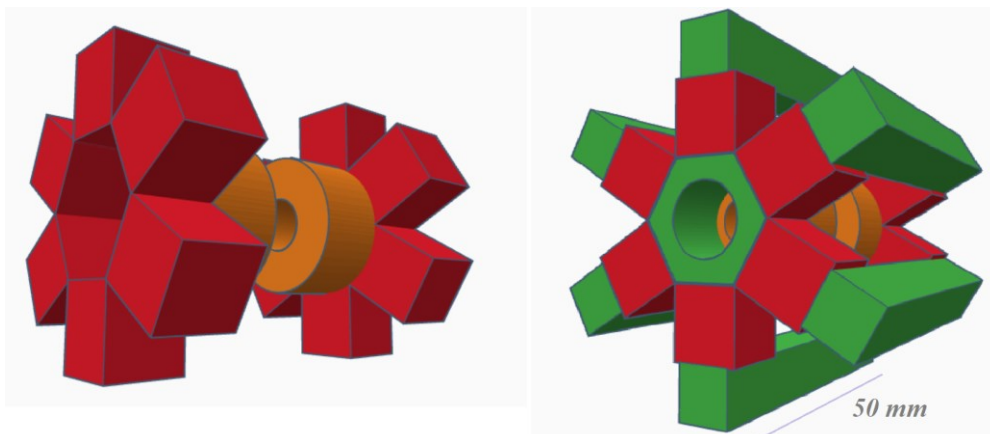


Figure 6. Magnetic arrangement of the INFN-Catania μ -EBIT. The strong magnetic field produced by the two central Nd-Fe-B ring magnets (orange) magnify the \mathbf{B} -flux at the center of the trap (0.4 T). The magnetic field is confined using twelve Nd elements (red) radially connecting the core of the trap to the soft iron bars (green) closing the magnetic yokes.

This design allowed us to easily map at the first order the magnetic field in the axisymmetric approximation by using the freely available Finite Element Method Magnetics (FEMM) package developed by David Meeker [24], at the same time a first prototype of the magnetic circuit was assembled to measure the field and validate the FEM simulations.

Figure 7 reports the preliminary \mathbf{B} -field FEMM calculations according to the μ -EBIT geometry, with respect to the proposed configuration, an additional soft iron element was added on-axis to shape the magnetic field at the cathode position (zero-field condition). The \mathbf{B} -field was measured by using a Hall probe moving axially in a step of 2 mm along the axis, subsequently also the radial field distribution at the center was measured to double-check the consistency of the simulations, thus probing the axisymmetric assumption.

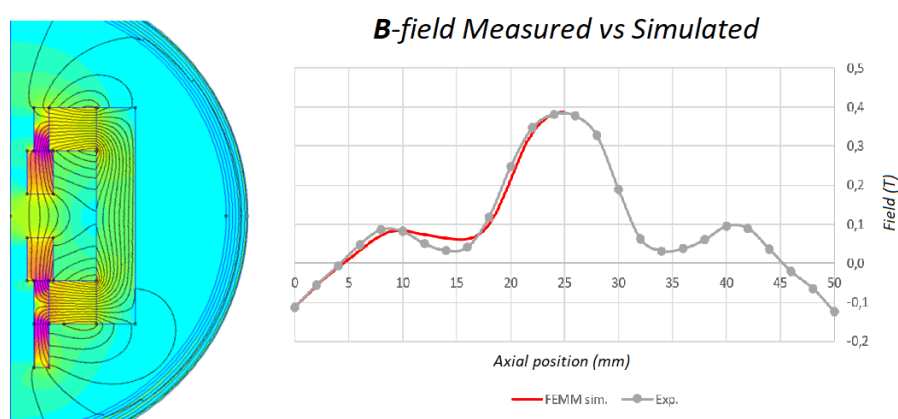


Figure 7. Preliminary \mathbf{B} -field axisymmetric FEMM simulation compared with on-axis measurements.

Once obtained these first-order magnetic field maps, we are proceeding by fine tuning the field, especially considering the axial cathode position and extraction point. Moreover, further work is in progress to better shape the field in the first 15 mm of the trap, where an inversion of the slope occurs, and e -beam acceleration takes place. To deduce the e -beam envelope, we have developed a MATLAB/OCTAVE [25] script for simulating the electron trajectories inside the trap. The script has been directly coupled with the FEMM field maps and it can run iteratively with the simulation code to converge towards an optimal \mathbf{B} -field distribution. First results show an e -beam compression ratio of 1/10 by using the preliminary field configuration. Further mechanical work is in progress to arrange the cathode in the zero-field position. More in detail, a set of e -microscope cathodes (mounted on AEI base) has been acquired by Kimball Physics [26]. As shown in Fig. 8 these are miniature cathodes with a disc size of less than 1 mm. For the specific purpose of testing the e -beam optics we have selected Ytria-coated Iridium cathodes as a good compromise between emission current and hardness to vacuum conditions.

ES-535 Ytria-coated Iridium Disc Cathode mounted on a standard AEI ceramic base



Figure 8. Miniature cathode by Kimball Physics [26], the ceramic base fits with the mechanical constraint of the μ -EBIT. The cathode will be axially moved along the EBIT for optimizing the e -beam envelope.

PERSPECTIVES

In addition to the limits of ECRIS we presented in the introduction, an advantage of EBIT with respect to other plasma devices is the possibility to highlight eventually nuclear transmutations from the changing of the emitted atomic spectrum. In fact, High Charge State Ion spectroscopy by EBIT has been selected at NIST as the best technique to measure the atomic parameters. In this context, the importance of laboratory plasma spectroscopy for astrophysical purposes is nowadays largely recognized [27,28].

As has been demonstrated, investigating nuclear decay-rates in-plasma establishes a frontier for the actual plasma-trap setup. Hot and cold plasma traps technology can be borrowed by atomic physics studies, in fact determining a cross-link between Coulomb and nuclear interactions studies. We would like to stress that this link is both technological and physical, since it is inherently embedded in astrophysics, i.e. in the star's core and in explosive nucleosynthesis. The possibility to explore these extreme environments on Earth is moving its first step right now. We start contributing to this new field by simplifying as much as possible the available tools, with the aim of stimulating and sustaining the new generations to move forward on this fascinating subject.

To this regard, we believe that the possibility to setup a simple and compact EBIT plasma trap is not a matter of high-cost projects, usually afforded by large labs or huge scientific communities. The μ -EBIT design was specifically conceived, and the development sustained by this concept.

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