JYFLTRAP: a Penning trap for precision mass spectroscopy and isobaric purification

T. Eronen\textsuperscript{a}, V.S. Kolhinen\textsuperscript{b}, D. Gorelov\textsuperscript{c}, J. Hakala\textsuperscript{d}, A. Jokinen\textsuperscript{e}, A. Kankainen\textsuperscript{d}, P. Karvonen\textsuperscript{f}, S. Kopecky\textsuperscript{d}, I.D. Moore\textsuperscript{g}, H. Penttilä\textsuperscript{d}, S. Rahaman\textsuperscript{e}, S. Rinta-Antila\textsuperscript{h}, J. Rissanen\textsuperscript{e}, A. Saastamoinen\textsuperscript{d}, J. Szerypo\textsuperscript{d}, C. Weber\textsuperscript{f}, and J. Äystö

University of Jyväskylä, P.O. Box 35 (YFL), FI-40014 University of Jyväskylä, Finland

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Abstract. In this article a comprehensive description and performance of the double Penning-trap setup JYFLTRAP will be detailed. The setup is designed for atomic mass measurements of both radioactive and stable ions and additionally serves as a very high-resolution mass separator. The setup is coupled to the IGISOL facility at the accelerator laboratory of the University of Jyväskylä. The trap has been online since 2003 and it was shut down in the summer of 2010 for relocation to the upgraded IGISOL facility. Numerous atomic mass and decay energy measurements have been performed using the time-of-flight ion-cyclotron resonance technique. The trap has also been used in several decay spectroscopy experiments as a high-resolution mass filter.

1 Introduction

Ion manipulation and trapping techniques have opened a new powerful way to study ground-state properties of stable and of short-living ions. Penning-trap mass spectrometry has become a routine technique for high-precision mass measurements and one can measure atomic masses of stable ions with a relative uncertainty $\delta m/m < 10^{-10}$ and short-living ions with $\delta m/m < 10^{-8}$ [1]. Uncertainties of this level allows to investigate many physics phenomena through atomic mass [2].

Stable-ion traps such as SMILETRAP in Stockholm [3], the trap setup at Florida State University [4] and the University of Washington Mass spectrometer (now at the Max-Planck-Institute for nuclear physics in Heidelberg, Germany) [5,6] have measured several masses of stable nuclei with precision of better than $10^{-10}$. Some of the high-precision results are actually used as reference masses for on-line Penning-trap setups. Also, Penning traps for anti-matter studies (e.g., ATRAP [7] and ASACUSA [8]) have performed high-precision mass measurements of anti-matter ions.

Most of the radioactive ion beam facilities that can provide beams of short-living ions have implemented a trap to be a part of their setup. Presently there are several functioning traps around the world which perform mass measurements with radioactive ions like CPT at ANL [9], ISOLTRAP at CERN [10], LEBIT at MSU [11], MLTRAP at LMU [12], SHIPTRAP at GSI [13], TITAN at TRIUMF [14], TRIGATRAP at the Mainz research reactor [15] and JYFLTRAP at the University of Jyväskylä [16,17]. These so-called on-line traps are typically very fast (they can access nuclei with short half-lives; see e.g., [18]) and also efficient in terms of very low production rates (see, e.g., [19]).

In this article the JYFLTRAP double Penning-trap setup will be described in detail. In short, the setup is designed to perform high-resolution beam purification and mass measurements with both stable- and radioactive-ion beams created with the Ion Guide Isotope Separator On-Line (IGISOL) technique [20,21].
Fig. 1. The experimental area of the IGISOL facility which is mostly occupied by the radiofrequency quadrupole (RFQ) cooler-buncher and the JYFLTRAP Penning-trap setup. Devices operated in high voltage are marked with (HV). The 30 keV ion beam from IGISOL (incident from right) is mass-separated with a 55° dipole magnet and deflected with an electrostatic 30° deflector to left towards the RFQ and JYFLTRAP setups. The setup is described in detail in sect. 3.

2 Basic principles

2.1 Ion beam production and separation

The JYFLTRAP setup receives beams from IGISOL, which is extensively discussed elsewhere in this special issue of the European Physical Journal A. The radioactive ions created either by fission or fusion reactions are stopped in helium gas, extracted by using electric fields and a helium gas jet via a sextupole ion guide (SPIG) [22], and are finally electrostatically accelerated to 30 keV of energy, where \( q \) is the charge state of ions (usually \( q = 1 \)). Alternatively, an electric discharge ion source can be used to create ions of stable isotopes (see, e.g., ref. [23] for more details). The extracted ion beam is mass-separated with a 55° dipole magnet (see fig. 1) allowing for a mass resolving power \((M/\Delta M)\) of about 500.

2.2 Radiofrequency quadrupole cooler-buncher

The mass-separated ion beam from IGISOL is injected into a radiofrequency quadrupole cooler-buncher (RFQ) [24]. The 30 keV ion beam is electrostatically decelerated to \( \sim 100 \) eV of energy by having the whole RFQ on a high-voltage (HV) platform. The decelerated beam then enters inside the quadrupole rod structure filled with helium buffer gas at low pressure. The ions are cooled by collisions with buffer gas atoms and collected in a potential well. The cooled ions are periodically released to the Penning traps as short, 10–15 \( \mu s \), bunches.

2.3 Principle of a Penning trap

In general, a Penning trap is a device to confine charged particles to a small volume with a static quadrupolar electric field and a homogeneous magnetic field. The electric potential in cylindrical coordinates \((z, \rho)\) is of the form

\[
V(z, \rho) = \frac{U_0}{4d^2} (2z^2 - \rho^2)
\]

where \( U_0 \) is the potential difference between the ring and endcap electrodes and \( d = \sqrt{2z_0^2 + r_0^2} \) is the characteristic trap parameter defined by the trap geometry: \( 2z_0 \) is the distance between endcap electrodes and \( r_0 \) is the inner radius of the ring electrode.

The trapped charged particles exhibit three different eigenmotions. One of the motions, called the axial motion with frequency \( \nu_z \), occurs along the magnetic field lines. The other two motions are in a plane perpendicular to the magnetic field and are commonly called radial motions. These can be distinguished by their frequencies \( \nu_- \) and \( \nu_+ \). The magnetron motion with the lower frequency \( \nu_- \) is almost mass independent. The second motion described by the reduced cyclotron frequency \( \nu_+ \), exhibits a mass dependence, and the sum of the two frequencies is given by the cyclotron frequency \( \nu_c \):

\[
\nu_- + \nu_+ = \nu_c = \frac{1}{2\pi m} \frac{q}{B}
\]

where \( q \) and \( m \) are the charge and mass of the ion, respectively, and \( B \) is the magnetic field. For an ion with \( A/q = 100 \) trapped in a 7 T magnetic field via a Penning trap (potential depth of the order of 100 V), the reduced
cyclotron frequency, the magnetron frequency, and the axial oscillation frequency are of the order of $\nu_+ \approx 1$ MHz, $\nu_- \approx 2$ kHz, and $\nu_z \approx 50$ kHz. It should be noted that eq. (2) is only valid in an ideal case where the quadrupolar electric field is fully harmonic and the magnetic field perfectly homogeneous. In the case of a real Penning trap a more robust relationship is the invariance theorem [25,26]

$$\nu_c^2 = \nu_+^2 + \nu_+^2 + \nu_z^2. \tag{3}$$

In fig. 2 the three eigenmotions in a Penning trap are illustrated.

One important aspect of many on-line Penning traps such as ISOLTRAP, SHIPTRAP, MLLTRAP and JYFLTRAP is ion motion damping in a gas-filled trap. Introducing buffer gas into the Penning trap will lead to a modification of the ion’s motion [27]. The interaction between the gas and the ions will decrease the oscillation amplitude in the axial direction and reduce the radius of the modified cyclotron motion. However, the radius of the magnetron motion will increase.

2.4 Excitation of the ion motion in a Penning trap

The operation principle of a Penning trap is based on the manipulation of the trap eigenmotions. This is achieved by applying RF signals to different trap electrodes. In the case of JYFLTRAP, the ring electrodes are eight-fold segmented for exciting the radial eigenmotions. The effect of these excitations to the motion of trapped ions depends on the excitation mode and the applied parameters: the frequency, the amplitude, the duration and the envelope of the RF field. At JYFLTRAP, the RF electric fields are applied either in a dipolar or in a quadrupolar mode.

In the dipolar excitation the frequency is applied to the two opposite segments of the central ring electrode in such a way that the segments have the same frequency and amplitude, but opposite phase. At JYFLTRAP, a simplified excitation scheme is used, where the RF signal is fed only to one quadrant (two neighboring octants) of the ring electrode, while applying a static voltage to the others. Dipolar excitations at eigenfrequencies can be used to excite one particular eigenmotion without affecting the other two. Typically, the dipolar excitation is applied at the mass-independent magnetron frequency $\nu_-$ or at the mass-dependent reduced cyclotron frequency $\nu_+$ to enlarge the radius of the corresponding motion, i.e., to move ions away from the trap center.

A quadrupolar excitation can be achieved by using four segments and applying voltages in such a way that opposite segments receive the same frequency, amplitude and phase, while the two other segments, that are in a 90° angle relative to the two first ones, receive the same frequency and amplitude but the opposite phase. Here also a simplified excitation scheme is used at JYFLTRAP by connecting two opposite quadrants (two octants) to the same RF signal, while applying a static voltage to the two other quadrants. This quadrupolar type excitation is usually called as a side-band excitation. When one applies quadrupolar excitation with the mass-dependent cyclotron frequency $\nu_{RF} = \nu_c = \frac{1}{2} \pi q m B^2$ the two radial eigenmotions are bound together and there is a continuous conversion from one motion to the other. Figure 3 illustrates the connections of the ring electrode during dipolar and quadrupolar excitations. A more detailed description of the operation principles of a Penning trap can be found, for example, in ref. [28].
2.5 Time-of-flight ion-cyclotron resonance technique

At JYFLTRAP, the cyclotron frequency \( (\nu_c) \) is determined with the time-of-flight ion-cyclotron resonance (TOF-ICR) technique [29,30] which is based on probing the cyclotron frequency in the trap and measuring the flight time of the ions from the trap to a microchannel plate (MCP) detector located outside the strong magnetic field, see fig. 1. This technique provides a universal and fast way to perform mass measurements with a relatively low number of ions.

Initially, a small number of ions (ideally just one since larger number induces frequency shifts due to their mutual interaction) is injected into the trap. Next, a dipolar excitation with the magnetron frequency \( \nu_m \) is applied which leads to an increased magnetron orbit of all ions. Subsequently quadrupolar excitation is then used to mass-selectively convert the magnetron motion into a modified cyclotron motion. Due to this conversion from the low-frequency magnetron motion to the high-frequency modified cyclotron motion (the difference in the frequency can be as large as 10\(^5\)), the radial energy \( E_r \) of the ions will be increased. Larger radial energy leads to stronger axial acceleration of ions in the gradient of the magnetic field after the extraction according to the equation

\[
F = -\mu (\nabla \cdot B) = -\frac{E_r}{B_0} \frac{\partial B(z)}{\partial z} \hat{z},
\]

where \( \mu = (E_r/B_0)\hat{z} \) is the magnetic moment of the ion; \( B_0 \) is the magnetic field at precision trap and \( E_r \) radial energy of the ion. The measurement procedure is then done by scanning the quadrupolar excitation frequency \( \nu_{RF} \) around the cyclotron frequency \( \nu_c \) and determining the frequency resulting in the shortest flight time from the trap to the MCP detector. The flight time can be calculated by using the formula

\[
T(\omega) = \int_0^{z_f} \frac{m}{\sqrt{2(E_0 - qU(z) - \mu B(z))}} dz,
\]

where \( E_0 \) is the initial axial kinetic energy of the ion, \( U(z) \) is the electrostatic potential and \( B(z) \) is the magnetic field along the flight path [30]. Figure 4 shows a typical TOF-ICR spectrum. The conversion from magnetron motion to modified cyclotron motion is periodic and the conversion rate depends on the excitation time \( T_{RF} \) and the amplitude \( U_{RF} \). To achieve full conversion after the excitation in resonance the values \( T_{RF} \) and \( U_{RF} \) must be carefully chosen. Once the values are experimentally found, their product is kept constant:

\[
T_{RF}U_{RF} = const.
\]

The value of this constant depends of the trap geometry (see eq. (1)) and has been experimentally determined to be 11.2 mVs for JYFLTRAP. This full conversion happens only at the frequency \( \nu_{RF} = \nu_c = \nu_m + \nu_c \). At other frequencies the conversion is only partial. The line width of the resonance is inversely proportional to the excitation time \( T_{RF} \), i.e., longer excitation time gives a better mass resolving power.

![Fig. 4. A time-of-flight ion-cyclotron resonance curve for \(^{54}\text{Co}\) ions (\(T_{1/2} \approx 200\) ms). An excitation time \( T_{RF} \) of 200 ms was used. The pixels represent detected ions; the shading is proportional to the number of detected ions.](image)

![Fig. 5. A time-of-flight ion-cyclotron resonance curve for \(^{54}\text{Co}\) ions (\(T_{1/2} \approx 200\) ms) obtained with Ramsey’s method of time-separated oscillatory fields. An excitation time pattern of 25-150-25 ms (On-Off-On) was used. It should be noted that this figure has twice the amount of scanned frequency points than fig. 4.](image)

2.5.1 Excitation with time-separated oscillatory fields

Excitation with time-separated oscillatory fields was introduced by N.F. Ramsey [31] and applied in Penning-trap mass spectrometry for the first time at ISOLTRAP [32]. Once the analytical form for the spectrum shape became available [33,34], this method has been routinely used in many trap facilities. Typically the time-separated oscillatory fields method is performed with two equally long RF-on periods interrupted with a certain time duration. It is important to retain phase coherence for the two RF-on periods. With the same statistics typically a factor of 2 to 3 better precision is obtained than with the conventional cyclotron frequency determination described previously. The main peak is 40% narrower but most of the enhancement is due to fact that more frequency scan points lie on high-slope parts of the curve than in the conventional resonance. Typically the quadrupole RF field is switched on for 20–50 ms, then off for 150–750 ms (mostly depending on the half-life of the ion of interest), and finally switched on for another 20–50 ms. Naturally, any excitation scheme must fulfill eq. (6) for “RF-on” periods in order for ions to undergo one full conversion from magnetron to modified cyclotron motion. A typical TOF-ICR curve obtained with time-separated oscillatory fields technique is shown in fig. 5. In order to unambiguously assign the center fringe
corresponding to $\nu_c$, a conventional TOF-ICR curve can be recorded.

One important application employing ion motion excitation with time-separated oscillatory fields is the so-called “Ramsey cleaning technique” [35] which is used in high-resolution mass separation. This method has been developed at JYFLTRAP and is described in detail in sect. 5.1.

3 The JYFLTRAP experimental setup

The JYFLTRAP consists of two Penning traps located inside the same superconducting solenoid. The ions are injected from the RFQ (see ref. [24] for more details). The RFQ cooler-buncher and JYFLTRAP are on a single 30 kV high-voltage platform. This way, the ion beam incident from IGISOL can be electrostatically slowed down. The ion bunches from the RFQ are ideal to be injected into the JYFLTRAP setup; they have energy and temporal spreads of less than 1 eV and 15 $\mu$s, respectively. The JYFLTRAP setup is shown in fig. 1. Marked with HV are the devices that are operated on a high-voltage platform. The ions are transferred from the RFQ to the Penning traps as an 800 eV ion beam. In the following subsections technical details of the JYFLTRAP setup are given.

3.1 Superconducting magnet

The most visible part of the JYFLTRAP setup is the superconducting magnet that creates the magnetic field of the Penning traps. It is an actively screened 7.0 T superconducting solenoid manufactured by Magnex Scientific Ltd. in the UK. The magnet has a 160 mm diameter warm bore. The generated field is fine-tuned both with superconducting shimming coils and with ferromagnetic metal strips placed around the bore tube in order to create two homogeneous 1 cm$^3$ field regions 10 cm apart from the center of the magnet. The relative homogeneity of the magnetic field ($\Delta B / B$) has been $\approx 0.4$ ppm in both traps after restarting the magnet in 2007. The superconducting solenoid is placed on a high-voltage platform along with all the trap electronics.

### Table 1. Typical voltages used at the injection ion optics and at the injection section of the trap. Voltages are given with respect to the purification trap ring electrode potential. Transfer section refers to the beam line section between RFQ and trap and Injection 1...3 to three cylindrical electrodes in front of the first trap electrode T1. See also table 2.

| Electrode   | Voltage (V) | Beam energy (qeV) |
|-------------|-------------|-------------------|
| Transfer section | $-800$ | 834 |
| Injection 1   | $-800$ | 834 |
| Injection 2   | $-390$ | 423 |
| Injection 3   | $-350$ | 384 |
| T1-T10       | $-340$ | 374 |
| T11-T12      | $-30$  | 64 |
Table 2. Axial lengths of the electrodes in the purification trap (in addition, there is a 0.5 mm gap between each electrode) together with the operating voltages for the three modes of operation. The “trapping” denotes voltages used when the ions are stored in the trap and “Inj.” and “Extr.” when ions are being injected or extracted from the trap, respectively. The potentials are given with respect to the ring electrode potential. See fig. 6 for positions of the electrodes.

| Electrode | Description           | L (mm) | trapping (V) | Inj. (V) | Extr. (V) |
|-----------|-----------------------|--------|--------------|----------|-----------|
| T13       | Diaphragm (d = 4 mm)  | 24     | +100         | -20      |           |
| T14       | Gas feeding endcap     | 21.5   | +100         | -20      |           |
| T15       | Endcap                | 22     | +100         | -20      |           |
| T16       | Endcap                | 22     | +100         | +30      |           |
| T17       | Correction 2           | 6.7    | +66          | +20      |           |
| T18       | Correction 1           | 12.8   | +17          | +20      |           |
| T19       | Ring                  | 18.5   | 0            | 0        | 0         |
| T20       | Correction 1           | 12.8   | +17          | -1       |           |
| T21       | Correction 2           | 6.7    | +66          | -5       |           |
| T22       | Endcap                | 22     | +100         | -5       |           |
| T23       | Endcap                | 22     | +100         | -5       |           |
| T24       | Diaphragm (d = 2 mm)  | 24.5   | +100         | -5       |           |

The stainless-steel (grade 316L) vacuum tube inside the bore is mounted with adjustable fasteners allowing alignment of the beam tube with respect to the magnetic field axis. The alignment was performed by inserting an electron source to the center of the magnet and guiding the two beams of electrons following the magnetic field lines through a set of narrow collimators placed on both sides of the trap center. The same alignment procedure was later adapted also at MLLTRAP and details of the alignment procedure can be found in ref. [12].

3.2 Trap structure

All vacuum chambers are built of grade 316L non-magnetic stainless steel using the con-flat (CF) flange standard. Two turbomolecular pumps of 880 l/s are located at the injection and at the extraction side of the magnet. The pressure in the vacuum volume of the Penning traps (without any gas load) is well below the lower limit of the Penning pressure gauge ($5 \times 10^{-9}$ mbar).

All electrodes not within the superconducting solenoid are made of either aluminium or of stainless steel. The electrodes within the solenoid forming the trap electric field are made of gold-plated oxygen-free copper and they are electrically isolated from each other by aluminium oxide insulators. In total about 50 gold-plated copper electrodes form a 1046 mm long electrode structure, see fig. 6. For ease of assembly, the electrodes are subdivided to seven segments held together with aluminium rods. Once the segments are interconnected the whole package can be inserted into the vacuum tube as one unit from the extraction side. All trap electrodes are cylindrical. These are much easier to manufacture than hyperbolic electrodes and also better vacuum can be achieved in the precision trap due to open geometry. Most of the electrodes have an inner diameter of 32 mm.

Each of the two cylindrical Penning traps of JYFLTRAP (see fig. 6) consists of an 8-fold split ring electrode (A), two-fold splitted inner correction electrodes B) on each side of the ring electrode, outer correction electrodes (C) and endcap electrodes (D) located next to the correction electrodes. The dimensions of the electrodes have been scaled from the ISOLTRAP purification trap [36–38]. The lengths of the ring electrode, the first and the second correction electrode and the endcap electrode are 18.5, 12.8, 6.7 and 44 mm, respectively, separated by 0.5 mm. The trap nearest to the RFQ is called the purification trap and is filled with dilute helium gas to enable the use of buffer-gas cooling of ions (see sect. 4 for more explanation). Gas flow to other sections of the system is minimized with the use of electrodes having narrow channels (see fig. 6 electrodes E and F). The other trap, commonly referred as the precision trap is located on the extraction side, 20 cm away from the purification trap center.

Table 1 shows the typical voltages used in the injection section of the trap. Tables 2 and 3 show the dimensions of the trap electrodes and trapping and extraction voltages applied in the purification and precision traps, respectively. The extraction side voltages when the trap is used for atomic mass measurements are given in table 4. When ions are extracted to the post-trap decay spectroscopy station, the voltages are somewhat different to optimally transfer ions further out from the trap setup.

The voltages to the trap electrodes are fed into the vacuum tube on both sides of the solenoid with so-called plug chambers. Each plug chamber houses three 500 V 10 pin feedthroughs connected via silver-plated copper wires into 30 evenly distributed sockets on the circumference of an insulating ring made of PEEK. At the ends of the trap structure there are similar rings with pins that fit into the sockets of the plug chambers. The trap electrodes are connected to the pins via silver-plated copper leads.
Table 3. Axial lengths of the electrodes in the precision trap (in addition, there is a 0.5 mm gap between each electrode) together with the operating voltages for three modes of operation. The “Trapping” denotes voltages used when ions are stored in the trap and “Inj.” and “Extr.” when ions are being injected or extracted from the trap, respectively. The potentials are given with respect to the ring electrode potential. It should be noted that the potential of the precision trap ring electrode is 4.2 V higher than the potential of the purification trap ring electrode. See fig. 6 for positions of the electrodes.

| Electrode | Description             | L (mm) | Trapping (V) | Inj. (V) | Extr. (V) |
|-----------|-------------------------|--------|--------------|----------|-----------|
| T25       | Diaphragm \((d = 2 \text{ mm})\) | 24.5   | +10          | −10      |           |
| T26       | Endcap                  | 22     | +10          | −10      |           |
| T27       | Endcap                  | 22     | +10          | −10      |           |
| T28       | Correction 2            | 6.7    | +6.6         | −10      |           |
| T29       | Correction 1            | 12.8   | +1.7         | −10      |           |
| T30       | Ring                    | 18.5   | 0            | 0        | 0         |
| T31       | Correction 1            | 12.8   | +1.7         | −1       |           |
| T32       | Correction 2            | 6.7    | +6.6         | −1       |           |
| T33       | Endcap                  | 22     | +10          | −1       |           |
| T34       | Endcap                  | 22     | +10          | −1       |           |
| T35       | Endcap                  | 22     | +10          | −1       |           |

Table 4. Typical voltages used at the extraction section of the trap. The electrode voltages above the single horizontal line are given with respect to the precision trap ring electrode. After “Extraction 2” electrode the ions are accelerated to 30 q keV. The voltages below the single horizontal line are given with respect to the ground potential.

| Electrode | Voltage (V) |
|-----------|-------------|
| T36       | −2          |
| T37       | −3          |
| T38       | −4          |
| Plug chamber el. | −100  |
| Extraction 1 | −150  |
| Extraction 2 | −1200 |
| Shield grid | −900  |
| Einzel 1  | +8000       |
| (Einzel 2  | +2500       |

3.3 Electronic devices

The electronic devices required to operate the Penning traps include DC power supplies, high-voltage switches and arbitrary waveform generators. In addition, a pulse pattern generator is used to generate 5 V \(\text{ON}\) and \(\text{OFF}\) TTL signals for the switches, waveform generators and other equipment requiring time-dependent operation.

3.3.1 Power supplies

DC power supplies from two manufacturers, ISEG Spezialelektronik GmbH and Spellman High Voltage Electronics Corporation, are used. The ISEG power supplies used in the setup are modular units having their own control electronics with 16 independent outputs and with a voltage range from −500 V to 0 V. All electrodes listed in tables 1, 2, 3, and 4 having voltages less than 500 V are connected to these units. The ISEG modules have better voltage stability than the Spellman ones. Other electrodes requiring more than 500 V are connected to Spellman power supplies. Each of these power supplies have one output whose output level is determined by a 0–10 V control signal. These control signals are provided by digital-to-analog (DAC) modules in modular I/O systems manufactured by WAGO Kontakttechnik GmbH & Co. The ISEG crate and WAGO I/O systems are connected to a computer by a Control Area Network (CAN) fieldbus via fiber optic repeaters. For a summary of the DC power supply modules, see table 5.

3.3.2 High-voltage switches

Ion samples are either injected, trapped in or extracted from the purification or precision trap by switching the voltages of electrodes from “injection” or “extraction” to “trapping” voltage levels or vice versa. For each switchable electrode two voltage outputs from the ISEG power supply are connected to a high-voltage switch. One ISEG output may supply voltage to multiple electrodes as shown in tables 2 and 3, for example, to the electrodes from T13 to T15 in “open” mode. The switches are controlled by TTL signals.

Two kinds of high-voltage switches have been used, one for the 100 V deep purification trap and one for the
Table 5. Summary of the DC power supply modules in use.

| Manufacturer | Model       | Outputs | \(V_{\text{max}}\) (kV) | \(I_{\text{max}}\) (mA) |
|--------------|-------------|---------|-------------------------|-------------------------|
| ISEG        | EHQ F005n  | 16      | −0.5                    | 0.25                    |
| Spellman    | MP5N       | 1       | −5                      | 2.0                     |
| Spellman    | MP10N      | 1       | −10                     | 1.0                     |
| Spellman    | MP5P       | 1       | 5                       | 2.0                     |
| Spellman    | MP20P      | 1       | 20                      | 0.5                     |
| Spellman    | MP40P      | 1       | 40                      | 0.2                     |

Table 6. Arbitrary waveform generators and their usage.

| Model    | Maximum frequency (MHz) | Connectivity |
|----------|-------------------------|--------------|
|          | Continuous | Burst start  |
| 33120A   | 15         | 5            | GPIB, RS232 |
| 33220A   | 20         | 6            | GPIB, Ethernet |
| 33250A   | 80         | 25           | GPIB, RS232 |

| ID | Trap | Type | Motion | Model | Mode             | Remark                     |
|----|------|------|--------|-------|------------------|----------------------------|
| RF1| 1    | Dipole | \(\nu_\perp\) | 33120A | Burst start      |                            |
| RF2| 1    | Quadrupole | \(\nu_\parallel\) | 33250A | Gated            |                            |
| RF3| 2    | Dipole | \(\nu_\perp\) | 33220A | Burst start      |                            |
| RF4| 2    | Quadrupole | \(\nu_\parallel\) | 33250A | Gated            | Fixed starting phase       |
|    |      |        |        |       | AM               | Ramsey excitation          |
| RF5| 2    | Dipole | \(\nu_\perp\) | 33120A | Gated            | Ramsey cleaning            |
| RF6| 2    | AM    |        | 33120A | Burst start      | AM of RF4                  |

10 V deep precision trap. The switch for the purification trap is based on a Supertex inc. HV20822 16-channel high-voltage analog switch integrated circuit, which has two sets of eight analog switches and two corresponding digital inputs for TTL signals. The switch for the precision trap has been designed using UC2707 dual channel power drivers for switching and HFBR-2524 fiber optical receivers to control switching. OPA445 precision amplifiers have been used to boost the low current outputs from the ISEG power supplies.

3.3.3 Arbitrary waveform generators

The segmented ring electrodes of the two traps are connected to arbitrary waveform generators through AC/DC coupling boxes consisting of one resistor and a capacitor. Three models manufactured by Agilent Technologies are in use: 31120A, 31220A and 33250A (see table 6). The major difference between these models is the maximum frequency in continuous and so-called burst start mode. A LAN/GPIB gateway made by Agilent Technologies is used to connect the waveform generators to a computer via Ethernet. A pair of Ethernet media convertors bridges the high-voltage platform and the ground via a pair of fiber optic cables.

Arbitrary waveform generators have a connector for a TTL input signal that can be used in two ways. In burst start mode the TTL signal determines when the generator outputs a predefined number of (sine) waveforms, for example, 17 periods of sine waveform with \(\nu = 1.7\) kHz suitable for the 10 ms long magnetron excitation in the purification trap. In gated mode the generator repeats a (sine) waveform as long as the TTL signal remains in the ON level. In addition, amplitude modulation (AM) used with a Ramsey type of excitation is possible via a separate input terminal. In this mode the starting phase of the excitation waveform is random but the phase is continuous for the excitation periods [39].

3.3.4 Pulse pattern generator

The high-voltage switches and RF generators require precise timing signals. A PCI-card named PulseBlaster (model PB24-32k) is installed to a computer in order to provide these TTL signals for timings. It has 24 output channels and a 100 MHz clock which translates to a pulse
Fig. 7. Quadrupole frequency scan in the purification trap for ions produced in proton-induced fission at $A = 99$. Cyclotron resonance frequencies $\nu_c$ for various products have been labeled and marked with dashed vertical lines. The isotopes and isomers close to the stable $^{99}$Ru are not fully resolved. A full width at half maximum ($\Delta \nu_{\text{FWHM}}$) of 30 Hz is obtained, corresponding to a mass resolving power $M/\Delta M \approx 30000$.

resolution of 10 ns. The program executed by the card can contain up to 32 768 instructions that can last from 90 ns to 1.4 years each.

Most of the outputs from the card are connected to fiber optic transmitters through a buffer circuit. At the other end of each fiber optic cable is a fiber optic receiver which provides TTL signals for example to a high-voltage switch or to an arbitrary waveform generator.

3.3.5 Time-of-flight measurement

The signal of the amplifier of the MCP detector is recorded by a Multichannel Scaler/Averager (MCS) — Model SR430— that is made by Stanford Research System. It has a built-in discriminator with a typical pulse pair resolution of 10 ns. In the most common scenario, the recording time is 1024 times the 0.64 ps bin width. A TTL timing signal from the pulse pattern generator signals the device when to start counting ions as a function of time. The MCS is connected to a computer via GPIB bus and a LAN/GPIB gateway.

4 Purification trap

The first of the JYFLTRAP Penning traps is called the purification trap. It is filled with helium gas and is used for isobaric purification of ion beam. Trapped ions are manipulated by applying multipole RF fields to the azimuthally split ring electrode. After an initial cooling period without excitation, an azimuthal dipole field with magnetron frequency $\nu_m$ is switched on for a short duration ($\approx 10$ ms). This increases the magnetron radius of all ions. The amplitude of the RF field is chosen so that no ion, upon extraction, can pass through the narrow channel of electrode E shown in fig. 6. After the azimuthal dipolar excitation, a quadrupole RF field with the cyclotron frequency of the ion of interest (see eq. (2)) is switched on. This excitation causes conversion from magnetron motion to modified cyclotron motion. Due to this, amplitudes of both the magnetron motion starts to decrease and also the modified cyclotron motion decreases in the presence of buffer gas, which will center the ions of interest in the trap. Therefore, a mass-selected beam can be extracted through a diaphragm out of the purification trap. The mass resolving power of the purification depends on the physical dimension of the diaphragm, on the buffer gas pressure and the amplitudes of the applied fields. At JYFLTRAP, a mass resolving power $M/\Delta M$ of the order of $10^5$ has been achieved, see fig. 7. More details are given in ref. [16].

5 Precision trap

The precision trap is geometrically almost identical to the purification trap. It is primarily used for high-precision atomic mass measurements employing time-of-flight ion-cyclotron resonance (TOF-ICR) technique [29,30], and secondarily for high-resolution beam purification [35] reaching a mass resolving power of $10^6$ or more.

5.1 High-resolution beam purification

If the mass resolving power of the purification trap is not sufficient to prepare monoisobaric (or monoisomeric) ion samples, the precision trap can be utilized to provide even better mass resolution. Typically $\Delta \nu_{\text{FWHM}}$ of $10 \ldots 20$ Hz (or slightly better with reduced transmission) can be reached with the purification trap. Here we give a brief description of a high-resolution cleaning method employing both the purification and the precision trap providing even better than $\sim 1$ Hz resolution. A more comprehensive discussion of this so-called “Ramsey cleaning method” is given in ref. [35].
Fig. 8. Dipole frequency scan near the $\nu_{\perp}$ frequency of $^{133}$Xe using 20-40-20 ms On-Off-On pattern for dipolar RF field. The two states of xenon are clearly separated. Other isotopes are also present due to low resolving power of the purification trap. Resolving power $M/\Delta M \approx 10^6$ is reached.

The high-resolution cleaning is performed only after the pre-purification with the purification trap. The pre-cleaned bunch of ions is captured to the precision trap where contaminant ions are excited to a larger cyclotron orbit while the ion of interest remains mostly unexcited. To boost the performance in both resolution and the required time, the contaminants are excited with a dipolar RF field employing Ramsey’s method of time-separated oscillatory fields technique [31]. Here, a short RF pulse (with constant amplitude) is applied. This pulse is followed by a waiting period after which an RF pulse with the same duration is applied again. It is important to preserve phase coherence for the both RF-on periods.

This method is relatively fast. To resolve ions having about 1 Hz cyclotron frequency difference typically less than 100 ms is needed for the excitation procedure in total. The ions of interest are allowed to gain some cyclotron motion in the excitation process since the ion bunch is sent back to the purification trap for recooling and recentering. On the way the contaminants hit the 2 mm electrode and thus will be completely removed. Once the ions have been properly recentered in the purification trap, they are sent back to precision trap for mass measurements or further downstream for decay spectroscopy experiments.

The state-of-the-art example of the purification process is the separation of the isomer in $^{133}$Xe at 233 keV, corresponding to 1.7 Hz cyclotron frequency difference at JYFLTRAP [40]. Here only 60 ms was used for the excitation process in the precision trap and all in all about 500 ms was needed to prepare a monoisomeric bunch of $^{133m}$Xe ions. A dipolar frequency scan in the precision trap plotted in fig. 8 showing the transmission of different ion species.

Without this cleaning method several experiments would have not been possible, such as the $Q$-value measurements of $^{54}$Co and $^{50}$Mn [41] which both have half-lives less than 300 ms. Other methods would have required much more time to separate the states [42].

Fig. 9. A magnetron phase-locking scan. The starting time of the dipolar excitation time scanned. On the vertical axis the magnetron orbit radius after RF dipolar excitation ($\rho^-(0)$) is plotted. The radius is obtained from fits to the resonance curves (see fig. 10 where resonances corresponding to delay times A and B are shown). The period of the magnetron motion is $\approx \frac{1}{170} \approx 5.9$ ms.

5.2 Time-of-flight ion-cyclotron resonance measurement

Here the steps required to perform high-precision cyclotron frequency measurement using time-of-flight ion-cyclotron (TOF-ICR) [29,30] are explained.

5.2.1 Magnetron excitation

The first step after capturing the monoisomeric bunch of ions to the precision trap is the magnetron radius expansion. This is done with a short dipole RF pulse at magnetron frequency of 170 Hz. It is important that the magnetron radius expansion prior to the quadrupolar excitation is the same for all ions, and more importantly, for all ion bunches. In order to eliminate bunch-to-bunch variations, the phase of the dipole rf field is fixed to the injection time of the ions [43]. This is called magnetron phase locking. Figure 9 shows a scan where the time between the ion injection and the start of the dipolar
excitation has been varied. After dipolar excitation, the quadrupolar excitation is switched on to convert the induced magnetron motion to cyclotron motion. Two TOF-ICR curves are shown in fig. 10. One with a delay time of 0.6 ms (marked with A) and one with 3.6 ms (marked with B). For case A, the excitation is in the opposite phase to the magnetron motion of the ions, and, for case B, they are in the same phase.

Thus, to ensure similar magnetron radii for all ion bunches it is important to lock the phase of the excitation. Its absolute value is less important, since a larger resonance effect can be accomplished by increasing the amplitude of the driving RF generator.

5.2.2 Quadrupolar excitation

After the magnetron excitation, the quadrupole excitation is switched on to mass-selectively convert the magnetron motion to cyclotron motion. The excitation duration $T_{RF}$ and the quadrupole RF field amplitude $V_{RF}$ are tuned so that one conversion from magnetron to cyclotron happens only at the resonance frequency $\nu_+ + \nu_-$. With other frequencies the conversion is only partial. The quadrupole RF field frequency ($\nu_{RF}$) is scanned over an interval including the cyclotron frequency $\nu_c$ of the ions.

6 Complete atomic mass measurement procedure

Penning-trap mass spectrometry provides cyclotron frequency ratios between the ions of interest and the reference ions. The frequency ratio is converted to a mass ratio using eq. (2). By using a reference with a well-known atomic mass, the mass of the ions of interest can be obtained precisely. The determination of frequency ratios is explained in the following.

6.1 Measurement pattern

An ion bunch goes through the following steps:
1) Accumulation in the RFQ.
2) Purification in the purification trap.
3) High-resolution cleaning in the precision trap (if needed).
4) Recooling and recentering in the purification trap.
5) Ion motion excitations in the precision trap.
6) TOF recording.

These steps are repeated for subsequent bunches using different quadrupolar excitation frequencies $\nu_{RF}$. The full procedure is shown in fig. 11. To maximize the efficiency, the RFQ and the Penning traps are operated in parallel, thus minimizing the measurement time needed. Once enough data are accumulated for the reference ions, the measurement is switched over to the ion species of interest. When enough data are obtained for the ions of interest, the reference ions are scanned again. This procedure is repeated as long as needed.

6.2 Interleaved scanning

The production rate for the ions of interest can be very poor so that most cycles have no detected ions. It may take several hours to gather sufficient statistics for data analysis. Thus, the time between two reference measurements will be long, and changes in the trap environment may cause shifts in the resonance frequency. The conditions of the measurements will be more similar when they are performed in almost parallel fashion.

Switching between two ion species is a simple operation during the measurements. The parameters requiring a change are limited to the following ones.

- Mass-dependent parameters, such as:
  1) IGISOL separator magnet;
  2) transportation time from the cooler to the purification trap;
  3) transportation time from the purification trap to the precision trap;
  4) the purification trap cyclotron frequency.
- Production-rate-dependent beam gate timing.
- Ramsey-cleaning parameters (if applicable).

Except for the separator magnet, the changes can be performed in less than a second. Changing IGISOL dipole separator magnet to transmit another mass number may take up to 15 seconds. Thus, it is not practical to change between the ion species after every measurement cycle (0.2–5 s). A measurement program, which switches between two ion species after one or more fully completed frequency sweeps (0.5–2 min), has been developed.
7 Trap performance and systematic studies

The trap performance has been extensively studied. Fluctuations and inhomogeneity of the magnetic field as well as mass-dependent and residual systematic errors related to JYFLTRAP have been investigated. In this section, different optimization procedures are described and systematic uncertainties quantified.

7.1 Magnetic-field fluctuations

Although the magnetic field of the superconducting magnet is actively screened, there are some fluctuations in the field. These are mostly caused by the varying temperature of the immediate surroundings of the superconducting magnet and pressure of the liquid-helium vessel of the magnet. Some effort has been put into the stabilization of the temperature by covering the high-voltage cage of the trap platform with plastic cover in order to minimize air flow through the setup. Exhaust helium from the magnet cryostat is released to the lab through a differential pressure valve that keeps a small overpressure in the magnet cryostat.

The fluctuations of the magnetic field have been characterized by continuously measuring the cyclotron frequency of the same ion species. For example, fig. 12 shows the cyclotron frequency of $^{57}\text{Fe}^+$ ions measured continuously for about 55 hours. The observed fluctuations are mostly due to changes in the magnetic field, but can include other effects.

Fig. 12. Cyclotron frequencies of $^{57}\text{Fe}^+$ ions measured continuously for about 55 hours in January 2009. Every datapoint consist of 22 minutes of collected data. Statistical uncertainty is about $3 \times 10^{-9}$ for each point. The fluctuations around 14:00–18:00 in January 28 were due to an opening of the entrance doors to outside in the experimental hall (the temperature outside was about $-5 ^\circ\text{C}$). The origin of the frequency deviation around 17:00 in January 29 is not known.

In frequency ratio (or mass) measurements the linear drifts are taken into account by interpolating the reference scans recorded right before and after the ion of interest. To account for short-term fluctuations, a long frequency scan such as shown in fig. 12 is subdivided to 22 min files. A real measurement process is simulated by taking three consecutive files, the first and the third for reference and the intermediate one for the ion of interest. A frequency value is interpolated from the references and compared to

Fig. 13. The standard deviations obtained for different time durations between two consecutive reference scans. A slope of $1.2(2) \times 10^{-11}$ min$^{-1}$ and y-axis crossing of $3.6(2) \times 10^{-9}$ are obtained. The inset shows the distribution of offsets for the first point (22 min). This figure is from ref. [44].
the measured value in order to obtain the offset $B - B_{\text{int}}$. The whole 55 hours of data are treated like this, and a distribution of offsets is obtained. Next, the data interval is increased to 44 minutes and so on. Finally, the standard deviations of the different distributions as a function of time interval are obtained as shown in fig. 13, where a line is fitted through the points.

In the absence of non-linear drifts, the distributions should be constant and correspond to the statistical uncertainty of the individual TOF-ICR curve fits. With non-linear drifts present, a positive slope is expected. The $y$-axis crossing resembles the statistical uncertainty of the individual fits. The data shown in fig. 13 are from January 2009. A similar measurement was done prior to the quenching of the superconducting magnet in 2007 and reported in ref. [44]. That time the slope was $3.2(2) \times 10^{-11} \text{min}^{-1}$, slightly larger than in 2009. To be on the conservative side, this larger value has been used in all JYFLTRAP measurements.

Non-linear drifts of the magnetic field at JYFLTRAP is a factor of two smaller than the ones reported from ISOLTRAP in 2003 [45] (since 2008 their magnet has been stabilized to level beyond their measurement sensitivity [46]). Compared to TRIGATRAP, their fluctuations are a factor of two higher than JYFLTRAP [47]. Non-linear drifts at SHIPTRAP were almost 20-fold worse than at JYFLTRAP but with their recent implementation of pressure and temperature stabilization system their fluctuations have set a record low value of $0.13 \times 10^{-11} \text{min}^{-1}$ [48]. LEBIT trap has implemented an additional coil to counter the field decay due to the magnet; the remaining non-linear fluctuations are of the order of $0.83 \times 10^{-11} \text{min}^{-1}$ [11] and Canadian Penning-trap reports $1.3 \times 10^{-11} \text{min}^{-1}$ [49].

If a measurement does not exceed 30 minutes at JYFLTRAP, the contribution from non-linear magnetic field drifts are below $1 \times 10^{-9}$ level. Since the shifts have no preferred direction, contribution from the magnetic field fluctuations are added to the statistical uncertainty.

### 7.2 Magnetic- and electric-field inhomogeneities

To minimize the effects of inhomogeneities of the magnetic field the volume in which the ions are confined should be as small as possible. Radially some expansion is needed for the TOF-ICR technique to work, but the amplitude of the axial motion should be minimized. Higher amplitudes result in the ions probing a larger extent of the magnetic field, especially in axial direction, where they are confined only by the electric potential. The axial extent can be minimized by optimizing the ion transfer time between the traps. With a non-optimal transfer time the ions gain energy in the transfer process. This can be observed only as a shorter time of flight of the ions when extracted from the trap but also in shifts of the measured cyclotron frequency. In fig. 14, the cyclotron frequency as a function of the transfer time is shown. With non-optimal times the frequency increases, indicating that the magnetic field is on average weaker at the center. This coincides with the shimming data of the magnet: The field was measured to be stronger on both sides of the center of the precision trap.

Both electric- and magnetic-field inhomogeneities could well be minimized by following the procedure described in [50]. Especially the electric field optimization will be performed in the new JYFLTRAP setup.

### 7.3 Carbon clusters cross-reference measurements

#### 7.3.1 Background

Mass measurements aim for better and better accuracies. As always in experimental science, this requires a better understanding of the measurement instrument. A detailed description of the device and its features has been given in the previous sections. In addition to this, also better, more accurate reference-mass ions are needed for more accurate mass measurements with Penning traps. Since the atomic mass unit (u) is defined as

\[
1 \text{u} = \frac{1}{12} m(^{12}\text{C}),
\]  

the carbon atom or a multiple of carbon atoms, a so-called carbon cluster, is an ideal reference mass ion. Carbon clusters are available in equidistant steps of 12 mass units practically covering the whole chart of nuclei. Therefore, carbon clusters are typically used both for systematic studies of the mass spectrometer and also as reference masses.

To study the performance of Penning-trap devices, a carbon-cluster ion source based on laser ablation has been used already at ISOLTRAP [45], at SHIPTRAP [51] and at TRIGATRAP [47] to quantify mass-dependent systematic effects.

The effort to build a carbon-cluster ion source for JYFLTRAP started around 2005. The first carbon-cluster ions were fired through the trap setup using the first version of the ion source described in ref. [52]. The ions
were produced in a setup situated in an extension of the 90° cross-chamber between the RFQ and Penning traps. The setup was closely related to JYFLTRAP and ISOLTRAP setups. The main difference to JYFLTRAP was the production of ions at the 30 kV high-voltage platform where the ion source was installed.

This place for the source had some clear advantages: the source could be built inside the same 30 kV platform without having a separate high-voltage installation. Also, switching between the carbon cluster source and the main IGISOL source would be easy by simply pulsing the electrodes of the quadrupole bender. Unfortunately, a good beam quality could not be achieved. The energy spread of the ions was far bigger than the depth of the purification trap (100 V) and carbon cluster ions of broad mass range were captured into the trap. Although this version of the cluster ion source could be used for some tests, it was decided to relocate the source further upstream of the RFQ or even before the IGISOL dipole magnet. This would allow an ideal, cooled reference ion beam identical to the beam of the ions of interest from IGISOL.

The ideal place for the carbon-cluster ion source would have been in the IGISOL cave in place of the main ion source. Here, the 55° dipole magnet could have been used to sieve only the cluster species with certain mass to charge ratio. Since IGISOL was almost in constant use by other experiments, this was not feasible. Finally, the ion source was built inside the electrostatic switchyard (at the IGISOL dipole separator magnet), see figs. 1 and 15. At the time there was only an electrostatic bender and a deflector unit inside the switchyard. Even without the full mass separation of the IGISOL dipole magnet, at least the modest mass-selectivity of the RFQ cooler buncher could be used.

7.3.2 Carbon cluster ion source
In short, the carbon cluster ion source consists of a carbon plate which is impinged by intense enough laser pulses that some clusters of carbon are evaporated and ionized (see fig. 15). The created ions are guided and accelerated with a set of electrodes to create a (bunched) beam. Here, a Q-switched Quantel Brilliant Nd:YAG 532 nm laser was used to create carbon ions from a Sigradur® glassy carbon plate. The laser operates at up to 10 Hz repetition rates. The laser spot is focused down to smaller than 1 mm diameter to achieve high enough energy densities for ablation. The carbon plate is situated on a rotating disk to ensure that the laser does not burn a hole through the plate. A more thorough description of the carbon-cluster ion source can be found in refs. [52,53].

7.3.3 Measurements and results
The cross-reference measurements were performed to quantify the mass-dependent frequency shifts. Since the mass ratios of carbon clusters are known, the shifts in frequency ratios can be quantified. In total more than 200 cyclotron frequency ratios were obtained. Three different sized cluster ions \(^{12}\text{C}_7^+, \, ^{12}\text{C}_10^+ \) and \( ^{12}\text{C}_{13}^+ \) were chosen as reference masses. These were measured against five to eight different sized clusters. To achieve better precision in determining the centre frequency, Ramsey excitation schemes were used. A full description of the measurement parameters can be found in ref. [53].

Two main systematic properties of the JYFLTRAP setup were quantified: the mass-dependent uncertainty and the so-called residual uncertainty. The mass-dependent uncertainty estimates the relative frequency
shift due to the difference in mass between the reference ion and the ion of interest. The residual uncertainty contains all the remaining systematic uncertainties of the setup.

The mass-dependent uncertainty was measured to be

\[ \sigma_m(r)/r = 7.8(3) \times 10^{-10} \times \frac{\Delta m[u]}{u}, \]

and the residual uncertainty

\[ \sigma_{res}(r)/r = 1.2 \times 10^{-8}, \]

where \( r \) is the measured cyclotron frequency ratio. With \( \Delta m \leq 24u \)—which is the case for all JYFLTRAP mass measurements performed so far—the uncertainties are

\[ \sigma_m(r)/r = 7.5(4) \times 10^{-10} \times \frac{\Delta m[u]}{u}, \]

\[ \sigma_{res}(r)/r = 7.9 \times 10^{-9}. \]

### 7.3.4 Future of carbon clusters at JYFLTRAP

The carbon cluster ion source that has been built and used for the systematic studies of the JYFLTRAP setup worked very well. Because it has to be manually removed from the beam line to inject beam from IGISOL into the trap, it was never used as a reference ion source. Building the high-voltage platform inside a vacuum chamber which was on the ground potential was not ideal. If the usual 30 kV potential was used, occasional sparks occurred between the platform and the ground potential. This was circumvented by using a slightly lowered high voltage than normal. This had no effect on the final systematic measurements and results.

Now that the whole IGISOL setup is moving to a different location, the systematic measurements should be at least partly repeated to confirm the good operation of JYFLTRAP. It is also a great opportunity to improve the cluster ion source itself.

A tentative location for the carbon-cluster ion source in the future is a separate off-line ion source station, located so that the mass-selection power of the dipole magnet can be used.

### 7.4 Mass doublets

Frequency ratio measurements of ions with same \( A/q \) ratio form a special class of JYFLTRAP measurements. Although frequency shifts due to electric field imperfections and tilt between electric and magnetic fields axis are present [54], the effect in the frequency ratio is negligible compared to statistical uncertainty.

Several mass doublet measurements have been done at JYFLTRAP. Mostly these are \( Q \)-value measurements of superallowed beta emitters [55] and of rare weak decays (see, e.g., [56,57]). In these measurements no residual systematic uncertainty as described in the previous section has been added, and precisions in the \( 10^{-9} \) range have been achieved. The mass differences of several mass doublets that are known to very high precision have been measured to check the reliability. These include \( ^{26}\text{Al} \), \( ^{34}\text{Cl} \) as reference, \( ^{34}\text{Cl} \) with \( ^{34}\text{Cl} \) as reference and \( ^{76}\text{Ge} \) with \( ^{76}\text{Se} \) as reference [23,58].

The doublet measurement technique gives a significant boost compared to “ordinary” mass measurements. In fig. 16 precisions obtained for superallowed \( \beta \) emitter \( ^{38}\text{Ca} \) in three trap facilities are given. In addition to JYFLTRAP, the \( Q \)-value was measured at ISOLTRAP (George 2007 [34]) and at LEBIT (Ringle 2007 [59]). Their measurements concentrated only on \( ^{38}\text{Ca} \) mass; mass of the daughter, \( ^{38}\text{K} \), was taken from the literature. LEBIT measurement was performed with doubly charged ions while ISOLTRAP measurement relied on Ramsey method. As seen, the JYFLTRAP result is at least 5 times more precise. Recently the doublet technique has been utilized at SHIPTRAP to measure \( Q \)-values of double-electron-capture candidates (see, e.g., [60,61]).

### 7.5 Present performance and limits

In terms of IGISOL production yields, the most exotic species so far measured are neutron-rich nuclei such as \( ^{122}\text{Pd} \), \( ^{114}\text{Tc} \) and \( ^{103}\text{Y} \). Their yields were less than 1 ion/s and half-lives about 100 ms [62].

The narrowest peak width achieved with the purification trap has been about 10 Hz (\( \Delta \nu_{FWHM} \)), which corresponds to a mass resolving power \( R = M/\Delta M \) of about \( 10^5 \) for singly charged \( A = 100 \) ions. With a moderate mass resolving power (\( \approx 10^4 \)) the transmission of the whole RFQ and trap line has been about 40%. This was measured using \( ^{62}\text{Ga} \) ions by measuring their decay rate with a silicon detector before the RFQ and after the Penning trap.

With the high-resolution cleaning method the best achieved FWHM so far is 1 Hz which corresponds to \( R = 10^9 \) for \( A = 100 \) ions. The transmission is very low when using high-resolution cleaning method: about 30 ions/bunch was demonstrated in ref. [40] although yield from IGISOL would have allowed much larger bunch sizes. Here the limiting factor is space charge in the precision trap.
8 Data analysis procedure

The recorded TOF-ICR data consist of the time of flight of the ions as a function of the frequency of the exciting RF field. The lineshape of the resonance curve is well described in ref. [30] for a rectangular excitation amplitude shape and in ref. [63] for time-separated oscillatory fields. Many aspects of the data analysis procedure have been elaborated at ISOLTRAP (see, e.g., [45]). More details about data analysis procedures at JYFLTRAP can be found in ref. [64].

8.1 Theoretical TOF determination

After quadrupolar excitation in the precision trap (as described in sect. 5.2.2) the extraction side potential wall of the trap is lowered and the ions are ejected towards the MCP detector, which is located at the ground potential, about 1.6 m downstream from the precision trap (see also fig. 1). The time of flight can be calculated since the magnitudes of the electric and magnetic fields are known from simulations. The electric potential along the geometry axis is shown in fig. 17, and the magnetic field in fig. 18. The fields are extracted from the ion optics simulation program SIMION, which gives the field values along the flight path with grid size of 1 mm. To make this less computer power demanding the fields are averaged over sections which can be described either with a constant number or, at most, with a second order polynomial. The full time of flight can then be calculated with eq. (5).

It is important to extract the ions slowly over the magnetic field gradient so that ions with more radial energy will gain significantly more axial energy when crossing the field gradient. At ≈ 600 mm the ions are electrostatically significantly accelerated. At this point the magnetic field is only about 0.1 T. The ions are then hitting the MCP detector with 30q keV of energy.

8.2 Determination of the experimental TOF and its uncertainty

Several bunches of ions are recorded for each frequency. A TOF gate is applied so that only ions within a certain TOF interval are accepted. The gate has to be set so that no ions of interest are left out. This is illustrated in fig. 19.
where the TOF gate has been set to be 155–330 μs (depicted with full vertical bars). Ions outside the gate do not contribute to the cyclotron frequency determination. Another gate is imposed by the number of detected ions. Typically, the analysis is performed by dividing the data into classes according to how many ions were detected in a single bunch. This is called countrate class analysis and is well described in ref. [45]. This way, the fitted frequency can be extracted as a function of detected ions per bunch. If contaminants are present, the frequency is expected to shift with increasing number of ions.

To calculate the TOF uncertainty at each frequency a so-called mean-corrected sum-statistics method is used in order to provide uncertainty even for the frequencies where only few ions were detected. In these cases ordinary standard deviation of the mean value would produce unrealistic uncertainties [64]. First, the mean TOF for each frequency point is calculated. Then, the distributions of each individual value. The inner and outer errors are calculated. The mass-dependent and residual systematic uncertainty are added at the very end.

![Diagram](image)

**Fig. 20.** Determination of a single frequency ratio using two reference ion scans and an ion-of-interest scan. The countrate class analysis is performed for each scan. Uncertainty due to the magnetic field fluctuation is added to frequency ratio.

8.3 Cyclotron frequency ratio determination

The ion-of-interest scans have been obtained consecutively or interleaved as described in sect. 6.2. The TOF-ICR curves are fitted using the countrate class analysis (see ref. [45]) to account for shifts due to contaminating ions. At JYFLTRAP, the MCP efficiency was measured to be about 60% [65] thus, in order to get a frequency value corresponding to one stored ion in the trap, the countrate classed results were extrapolated to a value of 0.6.

With consecutive scanning, where the ion species is switched every 30 minutes or more, the reference frequency needs to be interpolated from adjacent scans to the ion-of-interest scan. From the interpolated frequency and the ion-of-interest frequency the final cyclotron frequency ratio is obtained.

For a single measurement consisting of a reference scan (at time \( t_0 \) having frequency \( \nu_{\text{ref}} \)), an ion-of-interest scan (at time \( t_1 \) having frequency \( \nu_{\text{meas}} \)) and a reference scan again (at \( t_2 \) with \( \nu_2 \)), the interpolated reference ion frequency \( \nu_{\text{ref}} \) at the time of \( \nu_{\text{meas}} \) is

\[
\nu_{\text{ref}} = \frac{1}{t_2 - t_0} \left[ \nu_0 (t_2 - t_1) + \nu_2 (t_1 - t_0) \right],
\]

with uncertainty

\[
\sigma(\nu_{\text{ref}}) = \frac{1}{t_2 - t_0} \sqrt{(t_2 - t_1)^2 \sigma(\nu_0)^2 + (t_1 - t_0)^2 \sigma(\nu_2)^2}.
\]

After having both the interpolated reference frequency \( \nu_{\text{ref}} \) and the frequency of the ion of interest \( \nu_{\text{meas}} \), the frequency ratio \( r \) is

\[
r = \frac{\nu_{\text{ref}}}{\nu_{\text{meas}}},
\]

with uncertainty

\[
\sigma(r) = r \sqrt{\frac{\sigma(\nu_{\text{ref}})^2}{\nu_{\text{ref}}^2} + \frac{\sigma(\nu_{\text{meas}})^2}{\nu_{\text{meas}}^2}}.
\]
With interleaved scanning no interpolation is needed. Uncertainty due to magnetic field fluctuation is quadratically added to the frequency ratio uncertainty. The analysis steps are summarized in fig. 20.

When a chain of data (Ref-Meas-Ref-...-Meas-Ref) has been taken, the final frequency ratio is weighted average of the individual frequency ratios. With interleaved scanning procedure a long measurement is split to convenient chunks that consists usually of about 30 minutes of data. The mass-dependent uncertainty and the residual uncertainty are added in this point, as illustrated in fig. 21. So far any data obtained with JYFLTRAP has not been corrected with mass-dependent shift. Instead, this shift is added as an uncertainty. Additionally the Birge ratio \[ R = \frac{\text{int}}{\text{ext}} \] needs to be calculated. For this, both the inner error, \[
\sigma^2_{\text{int}} = \frac{1}{\sum_i \frac{1}{\sigma_i^2}},
\] and the outer error, \[
\sigma^2_{\text{ext}} = \frac{\sum_i \frac{1}{\sigma_i^2} (r_i - \bar{r})^2}{(n-1) \sum_i \frac{1}{\sigma_i^2}},
\] are needed \((r_i)\) are the individual frequency ratios and the Birge ratio is \(R = \sigma_{\text{ext}}/\sigma_{\text{int}}\) [66]. If both the inner and the outer errors are about equal, the fluctuation around the mean value is purely statistical. Common practise has been that if either of the error is larger, then the larger one is used as the final error. At this stage the mass dependent and residual systematic uncertainties are added (see fig. 21).

8.4 Mass and Q-value

Finally the atomic mass of the ion of interest \(m_{\text{meas}}\) is obtained (for singly charged ions and omitting binding energies of the missing electrons)

\[
m_{\text{meas}} = r \times (m_{\text{ref}} - m_e) + m_e,
\]

where \(m_e\) is mass of an electron. Mass uncertainty is

\[
\sigma(m_{\text{meas}}) = \sqrt{\sigma(r)^2(m_{\text{ref}} - m_e)^2 + \sigma(m_{\text{ref}})^2 r^2},
\]

where uncertainty of the electron mass as well as binding energies of the missing electrons are neglected.

Mass differences or Q-values are calculated for singly charged ions by using the relation

\[
Q = (m_{\text{meas}} - m_{\text{ref}})c^2 = (r-1)(m_{\text{ref}} - m_e)c^2 + \Delta B_e,
\]

where \(\Delta B_e\) term (with singly charged ions typically few eV) arises from the binding-energy difference of the missing atomic electrons. The Q-value uncertainty is

\[
\sigma(Q) = \sqrt{\sigma(r)^2(m_{\text{ref}} - m_e)^2 c^4 + \sigma(m_{\text{ref}} c^2)^2 (r-1)^2}.
\]
Table 7. List of isotopes whose mass has been measured with JYFLTRAP. References to publications have also been given.

| Z | Element | Mass numbers | References |
|---|---------|--------------|------------|
| 6 | C       | 10           | [77]       |
| 12 | Mg      | 23           | [78]       |
| 13 | Al      | 23, 26       | [78, 79]   |
| 14 | Si      | 26           | [80]       |
| 16 | S       | 30, 31       | [81, 82]   |
| 17 | Cl      | 34, 34m      | [58]       |
| 18 | Ar      | 34           | [77]       |
| 19 | K       | 38, 38m      | [58]       |
| 20 | Ca      | 38           | [77]       |
| 21 | Sc      | 42, 42m      | [79]       |
| 22 | Ti      | 42           | [83]       |
| 23 | V       | 46           | [79]       |
| 25 | Mn      | 50, 50m      | [41]       |
| 26 | Fe      | 56–57        | [84]       |
| 27 | Co      | 53, 53m, 54, 56 | [41, 84] |
| 28 | Ni      | 55–57, 70–73 | [84, 44]   |
| 29 | Cu      | 57–58, 62, 73, 75 | [84, 79, 85] |
| 30 | Zn      | 59–60, 62, 76–80 | [84, 79, 85] |
| 31 | Ga      | 62, 78–83    | [79, 85]   |
| 32 | Ge      | 76, 80–85    | [23, 85]   |
| 33 | As      | 81–87        | [85]       |
| 34 | Se      | 74, 84–89    | [57, 85]   |
| 35 | Br      | 85–92        | [86]       |
| 37 | Rb      | 94–97        | [86]       |
| 38 | Sr      | 95–100       | [87]       |
| 39 | Y       | 80–84, 95–103 | [88–90, 62] |
| 40 | Zr      | 83–88, 98–105 | [87–89] |
| 41 | Nb      | 85–88, 100–108 | [88, 90, 62] |
| 42 | Mo      | 88–89, 100, 102–111 | [89, 23, 87, 62] |
| 43 | Tc      | 88–92, 106–114 | [89, 91, 62] |
| 44 | Ru      | 90–94, 106–116 | [89, 91, 62] |
| 45 | Rh      | 92–95, 108–119 | [89, 91, 62] |
| 46 | Pd      | 94–99, 101, 112–122 | [89, 92, 91, 62] |
| 47 | Ag      | 100          | [92]       |
| 48 | Cd      | 101–105, 116 | [92, 93]   |
| 49 | In      | 102,104, 115 | [92, 94]   |
| 50 | Sn      | 104–108, 112 | [95, 56]   |
| 51 | Sb      | 106–110      | [95]       |
| 52 | Te      | 108–109, 130 | [95, 93]   |
| 53 | I       | 111          | [95]       |
| 54 | Xe      | 136          | [96]       |
| 58 | Ce      | 136          | [96]       |
| 60 | Nd      | 150          | [97]       |

when neglecting uncertainty of the electron mass and the atomic electron binding energies. Typically contribution from the reference mass uncertainty \( \sigma(m_{\text{ref}}) \) can also be omitted since for \( A/q \) doublets \((r - 1) < 10^{-3} \) and thus in most of the cases uncertainty in the \( Q \)-value can be simply written as

\[
\sigma(Q) \approx \sigma(r) \times (m_{\text{ref}} - m_e). \tag{24}
\]

Table 8. List of isotopes whose mass has been measured at JYFLTRAP but not yet published.

| Z | Element | Mass numbers |
|---|---------|--------------|
| 15 | P       | 29           |
| 24 | Cr      | 49           |
| 25 | Mn      | 49           |
| 41 | Nb      | 108          |
| 42 | Mo      | 92, 94–98, 100 |
| 43 | Tc      | 104–105      |
| 48 | Cd      | 121–128      |
| 49 | In      | 129, 131     |
| 50 | Sn      | 130–135      |
| 51 | Sb      | 131–136      |
| 52 | Te      | 130, 132–140 |

9 Summary of JYFLTRAP atomic mass measurements

The JYFLTRAP Penning-trap setup was operational since 2003 until June 2010 when the whole IGISOL facility, including JYFLTRAP, were shut down for relocation. The atomic masses of more than 200 short-living nuclei have been measured and published as summarized in table 7. Nearly 50 more have been measured which are expected to be published shortly, see table 8. An up-to-date list of the measured and published nuclei can be found from the JYFLTRAP website [67].

The atomic masses measured at JYFLTRAP are shown in fig. 22. The main areas of studies are (see for mass measurement references in tables 7 and 8):

- Nuclear structure at the n-rich side [68].
- Nuclear astrophysics (near \(^{58}\)Ni, rp and \(\nu p\) processes, SnSbTe cycle) [69–72].
- \(Q\)-values of superallowed \(0^+ \rightarrow 0^+\) \(\beta\) emitters [55].
- \(Q\)-values of mirror decays [73].
- Testing the Isobaric Mass Multiplet Equation (IMME) [74].
- \(Q\)-values of neutrinoless double–electron-capture candidates (2 EC) [75].
- \(Q\)-values for double-beta decay studies (2\(\beta\)) [76].

All \(Q\)-value measurements have measured as doublets and typically precision of better than 1 keV \((10^{-8})\) have been obtained.

The mass measurement program will be continued as soon as the relocation and upgrade of the IGISOL and JYFLTRAP setups are complete in 2012. Upgrades include, for instance, a new off-line ion source which can be operated independently of the IGISOL frontend, and optional beam ports between the RFQ and Penning traps for adding various devices such as a multi-reflection time-of-flight mass separator.
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