A cylindrical Penning trap for capture, mass selective cooling, and bunching of radioactive ion beams

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A Penning trap ion accumulator, cooler, and buncher for low energy ion beams has been developed for the ISOLTRAP mass spectrometer at ISOLDE/CERN. A cylindrical electrode configuration is used for the creation of a nested trapping potential. This is required for efficient accumulation of externally produced ions and for high mass selectivity by buffer gas cooling. The design goal of a mass resolving power of about $1 \cdot 10^5$ has been achieved. Isobar separation has been demonstrated for radioactive rare earth ion beams delivered by the ISOLDE on-line mass separator.

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Penning trap, mass separation, ion cooling, ion accumulation

1 Introduction

Precision mass measurements on exotic radioactive isotopes with Penning traps have particular requirements: An efficient transfer of ions from an external ion source into the trap has to be achieved since the exotic species are normally produced only in minute quantities. Furthermore, for obtaining a high accuracy in the mass determination the stored ions have to be cooled and the ion cloud should contain only one ion species. Only then systematic errors due to trap imperfections and due to ion-ion interaction can be kept low.

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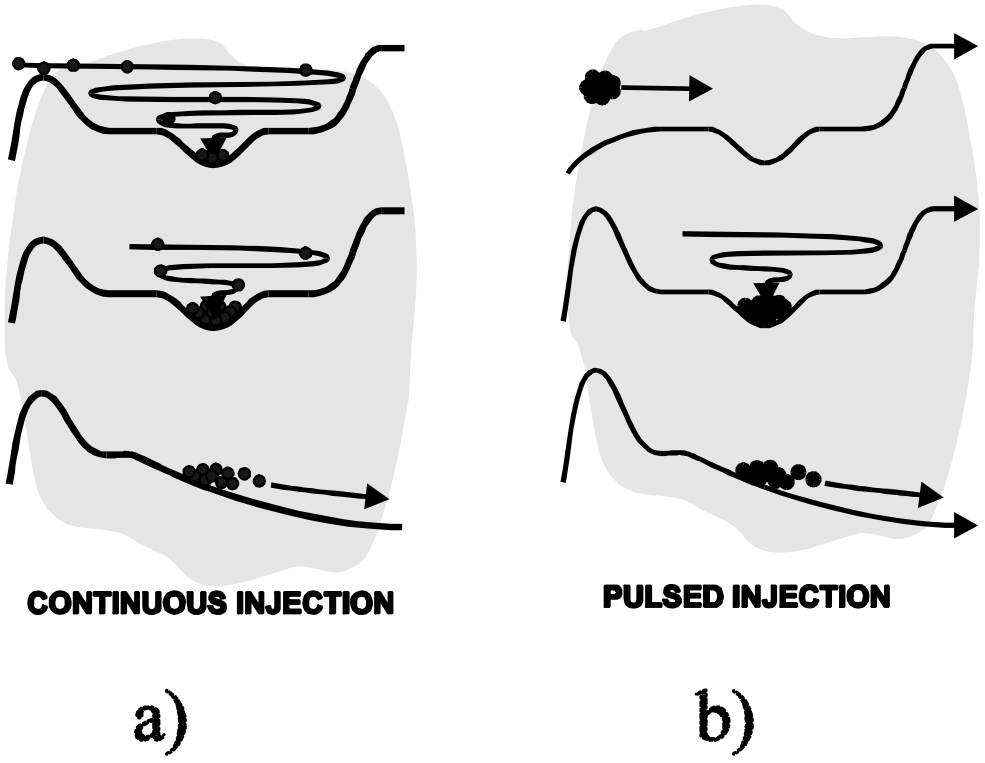

Fig. 1. Capture principle of continuous (a) and pulsed (b) ion beams in the cooler trap (see text)

The ISOLTRAP experiment at CERN [1] uses a Penning trap mass spectrometer for accurate mass measurements on radioactive isotopes delivered by the on-line mass separator ISOLDE [2]. Two Penning traps are used: one for the preparation of the ISOLDE ions, the other for the actual mass measurement via the determination of the cyclotron frequency of the ions. This article concentrates on the first trap of the ISOLTRAP system which has the task to prepare cooled ion bunches containing only one ion species. A mass selective buffer gas cooling technique, which assists the accumulation of the ions, allows to cool and to purify the stored ion cloud before it is transferred to the second trap. This cooling technique was developed within the ISOLTRAP experiment a few years ago and has already been tested and applied in a previous version of the set-up [1,3–5]. Based on this experience [1,4,5] a new cooler trap was constructed. The design aim was to reach high accumulation efficiencies for both continuous and pulsed beams, and a mass resolving power sufficient to separate isobars. The latter is essential for mass measurements on isotopes for which the ISOLDE ion source systems provide hardly any element selectivity and where several isobars are delivered simultaneously.

Table 1
Optimized lengths l_i and potentials V_i of the electrodes of the cylindrical Penning trap. The lengths are given in units of the inner radius r_0 of the trap elements, and the potentials in units of the potential difference between the ring electrode and the outer endcap electrodes.

electrode	V_i/V_0	l_i/r_0
upper endcap	0	4.00
upper correction electrode 2	0.34	0.45
upper correction electrode 1	0.83	0.83
ring electrode	1.00	1.19
lower correction electrode 1	0.83	0.83
lower correction electrode 2	0.34	0.45
lower endcap	0	4.00

2 Principle and concept of the new cooler trap

Two basic scenarii exist for the efficient transfer of an external ion beam into a trap and its conversion into a cold ion pulse which are illustrated in Fig. 1. In order to accumulate continuously delivered ions (Fig. 1a), they have to loose kinetic energy while passing through the trap. Such an energy loss can be achieved by a buffer gas. After a sufficient number of ions has been accumulated, cooled, and centered in the trap an ion bunch can be ejected by appropriate switching of the trap potential. In the case of a pulsed ion beam (Fig. 1b) dynamic trapping can be used, which means that the trapping potential is switched on when the ions have entered the trap [6]. Also here the presence of a buffer gas has advantages. Several ion bunches can be accumulated by capturing a new ion bunch after the previous has cooled into the trap center as illustrated in the figure.

Up to here only the longitudinal motion of the ions has been discussed. In the case of the transverse motion the situation is more complicated. Since the magnetron motion of an ion in a Penning trap is unstable the dissipating force provided by the buffer gas causes an increase of its amplitude. It has been shown earlier [4,5] that such an increase can be prevented by coupling the magnetron motion of the ion to its cyclotron motion. This can be achieved by exposing the stored ions to an azimuthal quadrupole rf-field at its cyclotron frequency $\nu_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$. This results in a centering of the ions, which is mass dependent since the cyclotron frequency is involved. It can therefore be employed for the elimination of unwanted ion species: a small diaphragm can be used to allow only ions close to the trap axis to be extracted form the trap.

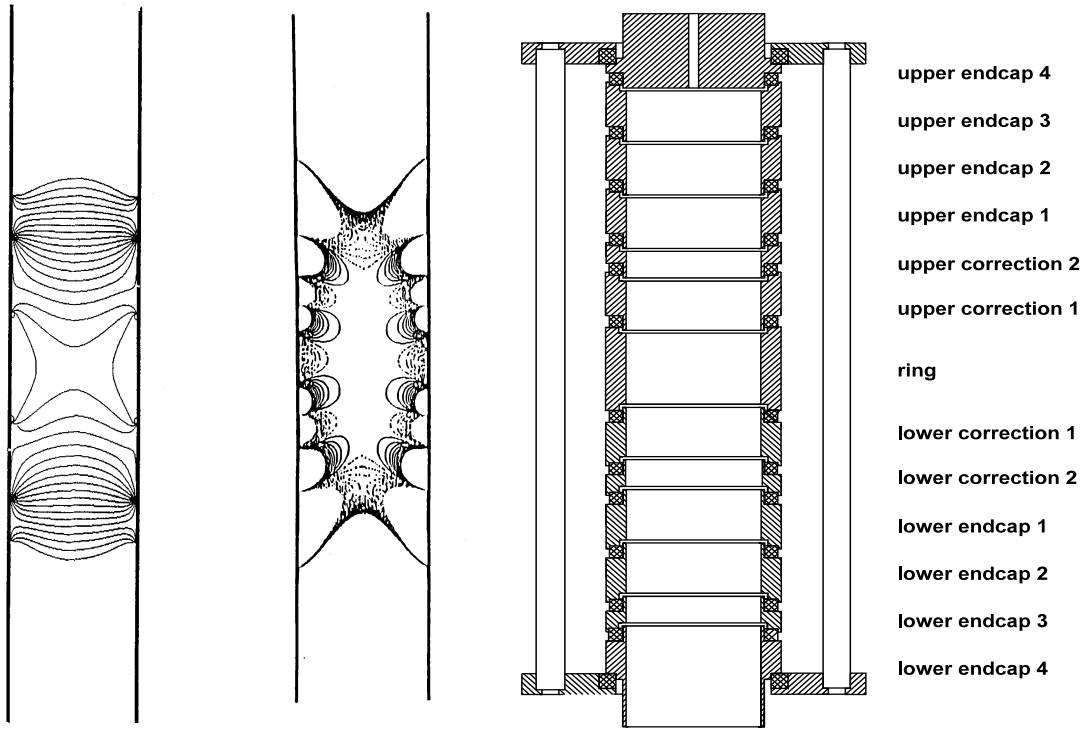

Fig. 2. Calculated trap potentials for the parameters given in Table 1 and the electrode configuration of the cooler trap (see text)

3 Design of the cooler trap for ISOLTRAP

A nested trap is the configuration of choice [7] as already indicated in Fig. 1. A large box shaped potential well is needed for an efficient ion capture. A good harmonic potential in the trap center is a prerequisite for avoiding frequency shifts in the ion motion which finally limit the achievable resolving power. Therefore, this trap region has to be designed carefully. For the creation of a nested trap potential a cylindrical electrode system can be used. The quality of the harmonic part of this potential depends on the number of electrodes, their length and the voltages applied to them. For the trap discussed here the following optimization procedure was applied: The electric potential produced by one ring segment of a given length between two infinite long cylinders is calculated by a relaxation method [3]. The total trap potential produced by a given configuration of electrodes is then calculated by a suitable superposition of the potentials produced by each electrode. Afterwards, the trap potential is analyzed along the trap axis in terms of a polynom expansion $V(z) \approx \frac{V_0}{2}\left(\frac{C_2}{d^2}z^2 + \frac{C_4}{d^4}z^4 + ...\right)$, where d is the characteristic dimension of the trap and V_0 is the trap depth, which is defined as the potential difference of the outermost electrode (endcap) to the central electrode (ring). In order to optimize the trap potential with respect to a good quadrupole potential

($C_2 = 1$, $C_{i>2} = 0$) the coefficients $C_{i>2}$ are optimization by a variation of the lengths and voltages of all electrodes.
Such an optimization was performed for several cylindrical trap configurations with an inner radius r_0. A rather large optimization range $-r_0 < z < r_0$ was chosen. The idea was to provide also for those ions a good harmonic potential which have not yet reached their lowest temperature. It was found that a five electrode system [7] would not fulfil the requirements. Therefore, a system of seven electrodes was chosen and optimized.
The final result of the numerical optimization of the lengths and voltages of the trap electrodes is summarized in Tab. 1. Analyzing the potential in the trap center and setting $C_2 = 1$ yields a characteristic trap dimension $d = 1.72\ r_0$. Figure 2a shows the equipotential lines for the optimized potential in the range $0.05 \leq V/V_0 \leq 0.95$ with a step size of 0.05. Figure 2b shows the deviation of this potential from a pure quadrupole. The equipotential lines for this difference potential cover the range $0.01 \leq V/V_0 \leq 0.01$ with a step size of 0.001. As can be seen from Fig. 2b the higher order (i>2) multipoles contributions are low in a volume characterized by $-r_0 \leq z \leq r_0$. A closer analysis shows that the most important higher order contribution is the octupole term with an expansion coefficient $C_4 < 0.1$.

With this value and typical experimental conditions (a magnetic field $B = 5\,\mathrm{T}$, an inner trap diameter $r_0 = 20\,\mathrm{mm}$, a trapping potential $V_0 = 10\,\mathrm{V}$, an ion with mass number A=100, and amplitudes of the cooled ions in the range of a few millimeters) it is found that the maximum frequency shifts are below $\Delta\nu_c/\nu_c < 10^{-6}$. Hence, electric field imperfections do not pose a limitation of the maximum achievable resolving power up to $R \approx 10^6$.

Based on these calculations a trap was constructed which is shown in Fig. 2c. The electrode structure has a length of $l = 240$ mm and an inner radius of $r_0 = 20$ mm. The trap electrodes, made of the aluminium alloy AlMgSi-05, are gold-plated. The electrodes are electrically insulated by rings made out of the glass ceramic MACOR. The electrode configuration consists of a ring electrode, four correction rings, and two endcap electrodes each consisting of four segments (upper/lower endcap 1-4). The upper endcap 4 has an inner radius of $r = 1.5$ mm. This acts as a diaphragm for differential pumping and allows only ions on the trap axis to leave the trap during ejection. For the creation of rf-fields as required for the excitation of the ion motion, the ring electrode is azimuthally divided into eight, and the upper and lower correction rings into four segments. The buffer gas enters the trap via an insulated Teflon tube at the upper endcap 1. The whole electrode assembly is carefully centered on two discs which are held together by four rods. The discs fit tightly into the honed vacuum tube made out of selected non-magnetic stainless steel. The tube itself is installed in the bore of a 4.7 T superconducting solenoid (Oxford Instruments, system 200/130). The cooler trap is placed in the ISOLTRAP set-up between the ion collector device and the high-precision mass spectrom-

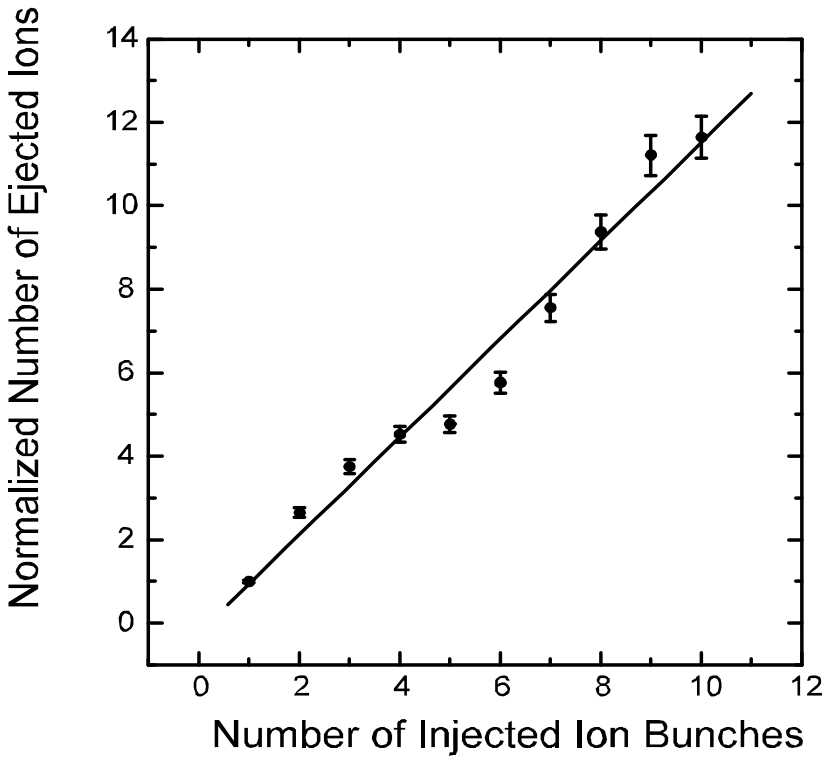

Fig. 3. Number of ejected and detected ions versus the number of collected ion pulses.

eter. A description of the ISOLTRAP spectrometer is given elsewhere in these conference proceedings [8]. Differential pumping sections below and above the trap allows a high buffer gas pressure ($p_{He} \leq 10^{-3}$ mbar) inside the cooler trap without disturbing the high vacuum requirements in other parts of the set-up. An ion optical system with electrostatic lenses, deflectors and transfer sections guides the ions from the ion source into the cooler trap and from the cooler trap into the mass spectrometer. For testing purposes a movable multichannel plate detector (MCP) is installed above the cooler trap.

4 Performance of the cooler trap

The principle of dynamic trapping and stacking of ions into the new trap system was investigated by using a Nd:YAG laser beam for the production of short ion bunches via pulsed laser desorption. As an example, Fig. 3 shows the result of successful stacking of ion pulses in the trap. Shown is the number of ions ejected as a single ion bunch out of the trap versus the number of injected and accumulated pulses. The repetition rate of the laser was 10 Hz and a helium buffergas pressure of about $1 \cdot 10^{-5}$ mbar was used inside the trap. The linear increase shows that no ion loss occurs during the stacking process.

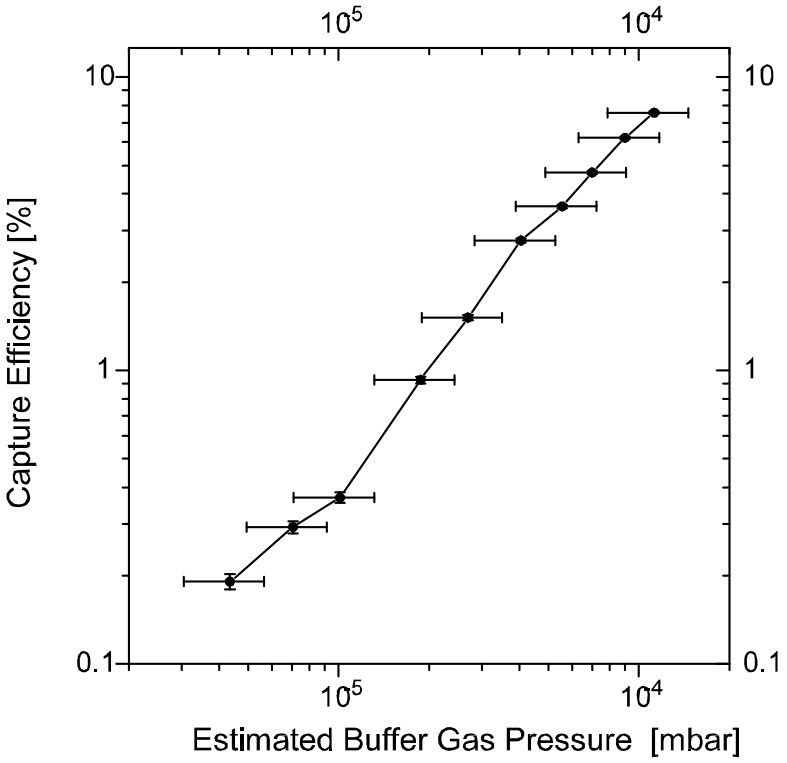

Fig. 4. Capture efficiency for a continuous ion beam as a function of the buffer gas pressure inside the trap.

The dependence of the capture efficiency of a continuous ion beam on the buffer gas pressure was measured with a thermal rubidium ion beam produced by surface ionization on a continuously heated rhenium foil. The ion beam was switched on for periods of $T = 10$ ms in order to allow a well defined number of ions to enter the trap. After storage and cooling for $T = 200$ ms, the ions were ejected and detected by the MCP detector. From the ratio of the number of detected ions to the number of ions entering the trap, the capture efficiency can be calculated. Figure 4 shows the measured efficiency as a function of the helium buffer gas pressure inside the trap. A linear increase of the capture efficiency up to 10% is observed for a pressure of up to $p_{He} \approx 10^{-4}$ mbar. The observed behaviour is found to be in agreement with energy loss calculations.

In order to test the resolving power and the performance of the cooler trap as a high resolution mass separator the 60 keV ISOLDE beam was used and collected for a short time on a rhenium foil. By heating the foil the accumulated atoms are released and re-ionized by surface ionization. These low energy ions are transferred into the cooler trap, typically operated at $p_{He} \approx 1 \cdot 10^{-5}$ mbar. After a cooling period of typically 200 ms all ions are driven to orbits larger than the diameter of the extraction hole of the trap. This is accomplished by a short excitation of the ion motion at the magnetron frequency of the ions, which is practically mass independent. Subsequently the ions are exposed to a quadrupole rf-field at a frequency ν_{rf} for a period of $T \approx 240$ ms. If $\nu_{rf} = \nu_c$,

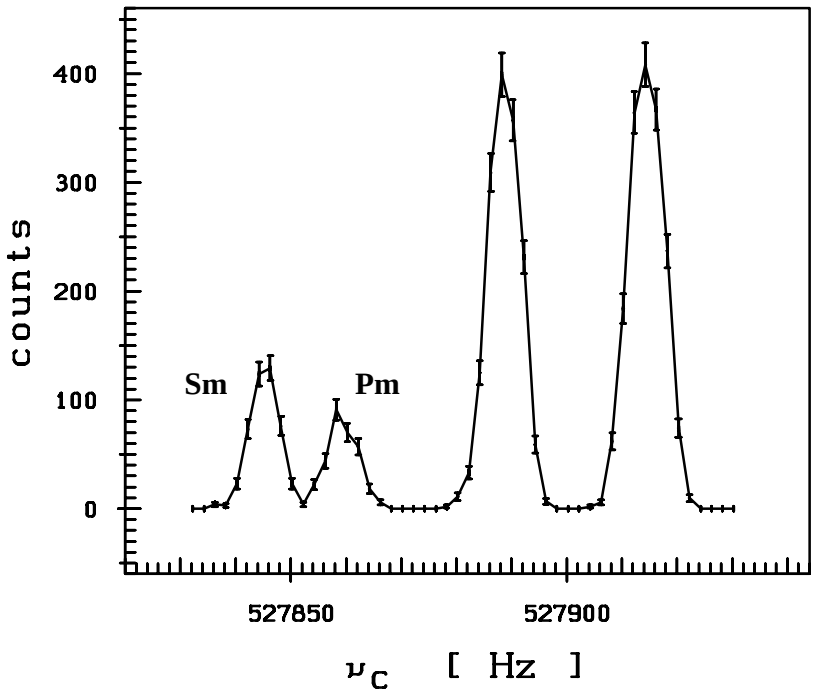

Fig. 5. Mass scan with the cooler trap for rare earth ions with mass number A=138. Shown is the number of ejected ions as a function of the applied rf-frequency.

the ions with this particular cyclotron frequency are recentered onto the trap axis while other ions with different mass (and therefore different cyclotron frequency) diffuse to even larger orbits. Finally those ions which have been recentered are ejected as a pulse through the small hole in the upper endcap. These ions are either transferred into the second trap of the ISOLTRAP setup or sent to the MCP detector above the cooler trap.

Figure 5 shows the result of a 'mass scan' on radioactive ISOLDE ions with mass number A=138. Shown is the number of ions ejected out of the cooler trap as a function of the applied frequency ν_{rf}. Five peaks are observed in this mass scan. The leftmost ones correspond to the isobars ^{138}Sm and ^{138}Pm. The remaining peaks contain mixtures of lighter unresolved isobars which are close to the valley of stability. The observed width of the resonances is $\Delta\nu(FWHM) \sim 7Hz$ which corresponds to a resolving power of R$\sim 10^5$. This measurement demonstrates that already a few nucleons away from stability isobar separation can be achieved. This feature of the cooler trap allowed for the first time direct mass measurement on radioactive rare earth elements. Meanwhile ISOLTRAP has performed accurate mass measurements on more than 40 radioactive isotopes in this region. The results are presented in [9].

5 Summary and Outlook

A cylindrical Penning trap has been developed which combines high capture efficiency and mass selective cooling of externally produced ion beams. Such a system has been installed at the ISOLTRAP mass spectrometer in order to accumulate, bunch, and purify the radioactive ISOLDE ion beam. Capture efficiencies of up to 10% have been achieved with continuous ion beams. Stacking of several ion pulses has been demonstrated. A mass resolving power close to 10^5 has been obtained, which is sufficient to separate isobars in many cases.
The concept of using a gas filled Penning trap for accumulation, cooling and mass separation is now also being applied in commercial Fourier transform ion cyclotron resonance (FT-ICR) spectrometers used mainly by chemists [10] and gains also importance in ion beam handling. For example a cylindrical Penning trap is foreseen in the REX-ISOLDE post-accelerator project [11] for cooling and bunching of the continuous ISOLDE ion beam prior to charge-state breeding and final acceleration. Furthermore is the installation of a similar Penning trap system is planned at the IGISOL system in Jyväskylä for an improvement of the beam properties.

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