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Ion manipulation with cooled and bunched beams

G. Savard[a]

Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA and Department of Physics, University of Chicago, Chicago, IL 60637, USA

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Abstract. Ion beam properties are often critical to experiments with rare isotopes. The ability to cool transverse motion and energy spread in a beam or modify its time structure can significantly improve many types of experiments. This ability is now a common feature in existing low-energy facilities and will play a central role in a number of next generation radioactive beam facilities. The basic physics underpinning the operation of these beam cooling devices is introduced below together with the key technical evolutions that have occurred since the previous ENAM conference. Examples of operating devices for various sources of radioactive ions are given, together with the performance presently achieved and improvements expected in the near future.

PACS. 29.25.Rm Sources of radioactive nuclei – 41.85.Ja Beam transport – 29.27.Fh Beam characteristics

1 Introduction

Ion beam properties determine to a large degree what experiments are possible with rare isotopes. Beam properties are many faceted, including beam intensity and purity, energy spread, size, angular divergence and time structure. And although experimentalists and machine physicists often concentrate on the beam intensity, perhaps because it is the easiest parameter to measure, it is but one of the factors that can affect an experiment. Other properties often also have a significant impact and the ability to cool transverse motion or energy spread, or modify the time structure of a beam, can yield significant improvements in resolution or signal to noise for many types of experiments. This ability has seen significant progress over the last decade, driven to a large degree by technical developments from the field of ion trapping. It is now a common feature in existing low-energy facilities and is expected to play a central role in a number of next generation radioactive beam facilities.

The techniques used rely on the efficient injection of the ion beams into large acceptance electromagnetic devices that confine and guide them in two or three dimensions while collisions with a low-pressure high-purity buffer gas reduces the energy (and energy spread) and concentrates the beam at the bottom of the confining potential. These new devices (ion coolers, isobar separators, gas catchers and so on) perform multiple tasks ranging from transverse cooling to bunching and purification of beams and can now even transform recoils from fission, low-energy nuclear reactions or fragmentation reactions into beams of ISOL-type quality. The basic physics underpinning the operation of these various devices is common and will be introduced in the following, together with the key technical evolutions that have occurred since the previous ENAM conference. The cooling of beams from three common sources of radioactive ions will be treated in some detail, presenting the types of cooling devices required, the performance presently achieved and improvements expected in the near future.

2 Cooling radioactive ion beams

Radioactive isotopes are produced typically in hostile environments. They are created in limited quantities and, as a result, extraction techniques must emphasize production rate and not beam quality. This often results in beams with poor ion optical properties. Radioactive isotopes are also often accompanied by contamination from other radioactive isotopes produced simultaneously and much more abundant stable isotopes.

Experiments with radioactive beams on the other hand usually benefit from, and in many cases require, high purity beams with good geometrical and timing properties. These requirements can manifest themselves in many forms. A low energy spread is critical for experiments such as collinear laser spectroscopy since the energy spread is directly correlated to the resolution of the measurement. The transverse beam properties, more specifically the transverse emittance of the beams, are critical in determining the transmission and resolution through a mass

[a] e-mail: savard@anl.gov

separator or a convoluted beamline. The duty cycle or time structure of a beam also determines our ability to capture this beam in ion traps or accelerate it in pulsed accelerating structures. The majority of experiments become more difficult when significant beam contamination is present, either because of decreased signal to noise or just because the additional count rate can overwhelm the detector system.

Essentially, each experiment has optimal beam properties that best suit it. The optimum production method for a given isotope will yield beams with properties that will often be different from the optimum properties required for the given experiment. Ion beam manipulation via cooling, bunching and purifying is the means that allows better experiments to be performed by matching the properties of the produced beam with that of the required beam.

2.1 Ion beam properties

The manipulation of beam properties can be performed by very simple means: a simple lens focusing a beam changes both the beam envelope size and its divergence. Similarly, passage through an RF accelerating gap will change both the energy and time structure of the beam. Although individual properties of the beam, such as transverse position or transverse momentum, are modified by such actions, one can define other beam properties that are not affected by them. These properties are the phase-space densities of the beam, determined by the products of conjugate variables such as position and momentum, or energy and time, in the transverse or longitudinal directions. They are essentially equivalent to an excitation temperature for the different degrees of freedom of the beam particles in the frame of the moving beam, expressed usually in term of longitudinal or transverse emittance, and that cannot be reduced or increased unless "heat" is removed from or added to the system. As a result, transverse focusing, time focusing, electrostatic acceleration and many similar types of ion beam manipulation steps are called non-dissipative; they can affect external beam properties but cannot change the intrinsic excitation energy of the beam (this is one form of Liouville's theorem).

On the experimentalist end of things, spectrometers, beamlines and experimental devices have an acceptance that can be expressed in similar terms. The maximum efficiency that can be obtained in transporting the ion beam through a beamline, spectrometer or apparatus can then be determined from the emittance of the produced beam and the acceptance of the device the beam must go through. If the beam emittance is smaller than the acceptance of the device then, in principle, non-dissipative transformations of the beam such as focusing can be applied to match the beam into the device; no "cooling" of the beam is required. Consider a device which has an entrance aperture of 5 mm and can accept a maximum beam particle angle of 10 mrad. Since in a focusing transformation the product of beam diameter and divergence remains constant we find that a beam with a diameter of 20 mm but a maximum beam particle angle of only 2 mrad can be focused to a diameter of 5 mm and a maximum angle of 8 mrad and all particles will be accepted by the device. If, on the other hand, the beam with diameter 20 mm has a maximum beam particle angle of 4 mrad then when focused to 5 mm, it will have a maximum angle of 16 mrad and it is not possible by non-dissipative transformation to obtain full transmission. Similar arguments can be used for the relation between beam pulse duration and energy spread, or for accumulation of DC beams in pulsed devices. If the emittance is larger than the acceptance, then no non-dissipative manipulation can yield the full efficiency and one must resort to dissipative forces to obtain high efficiency, *i.e.* cooling.

A cautionary note must be added here in that the conserved quantities are the phase space densities, such as the product of the transverse position and transverse momentum. The emittance is obtained from the product of transverse position and transverse angle (which is the ratio of the transverse momentum to longitudinal momentum). The emittance is a conserved quantity at a given energy but decreases as the longitudinal momentum is increased by acceleration for example. Multiplying the emittance by the longitudinal momentum yields the proper conserved quantity. This is the principle behind the so-called normalized emittance (emittance times the velocity β) which is a conserved quantity during acceleration and is often used to compare emittance or acceptance at various energies. Finally, ion beams do not have precisely defined boundaries but rather envelopes defined to contain a given fraction of the beam particles. This fact, although important, adds complications to the concept of emittance that are not critical to our discussion and will be neglected here.

2.2 Basic ion cooling principles

The action of cooling corresponds to decreasing the phase-space occupied by an ensemble of particles, or, if that ensemble is moving at a common velocity large compared to the relative velocities (*i.e.* if it forms a beam), to decreasing the emittance of this beam. To perform cooling or bunching, a few basic requirements must be met:

- to have a cold thermal bath (cold electrons, buffer gas, laser beam, ...);
- to have an interaction between your ensemble or ion beam and the cold thermal bath;
- to have sufficient acceptance of the bath, interaction time with the bath and thermal capacity of the bath;
- to have the ability to extract the ions from the bath without substantial reheating.

Numerous thermal baths are available that offer varying advantages depending on the species and properties to be cooled. For the sake of simplicity, the discussion will be limited here to the most frequently used technique that can be applied to essentially any ion species: collisions with a buffer gas in a trapping/guiding structure. In this case the buffer gas provides the thermal bath, collisions are the means of interaction to exchange heat between the ions and the gas, and guiding/trapping structures are

Fig. 1. Examples of RF structures available for the confinement and manipulation of charged particles. From left to right we find the standard Paul trap configuration, the RF quadrupole, the RF hexapole, and an RF wall. In the Paul trap the RF is applied between the ring and the two endcaps. In the other structures, the RF is applied between adjacent rods.

most often used to provide large interaction time and localization. The conditions to be met here are that there be enough stopping/cooling power to capture the ions in the longitudinal potential within the length of the device, and that it has a large enough guiding/trapping potential and volume to accept the initial transverse emittance and energy spread. These conditions ensure that the ions spend enough time in contact with the gas to be cooled to its temperature.

2.3 Available confinement devices

A key issue in cooling ion beams is the choice of a confinement structure that is best suited to the properties of the incoming ions. In general, these are derived from ion traps which are devices aimed at storing ions for extended time. The most versatile confinement devices use RF focusing. The basic operating principle behind RF focusing devices can be understood most easily if we consider only motion in one dimension. In an inhomogeneous RF field, the electric field along the z-axis can be expressed, for small displacements d around a point z_0 ($z(t) = z_0 + d(t)$), as

$$E(z,t) = E_0(z)\cos\omega t = \left[E_0(z_0) + d\left(\frac{\partial E_0}{\partial z}\right)\right]\cos\omega t\,. \tag{1}$$

The motion on an ion of charge e in this oscillating electric field is given by

$$F_z(t) = m\ddot{z} = eE_0(z)\cos\omega t \tag{2}$$

and for small oscillation amplitude, the position of the ion is given by

$$d(t) = z_0 - d_0\cos\omega t \tag{3}$$

with

$$d_0 = \frac{eE_0}{m\omega^2}. \tag{4}$$

Averaging the force on the ion over a full RF cycle yields

$$\langle F_z(t)\rangle_{\rm av} = e\left(\frac{\partial E_0(z)}{\partial z}\right)\langle -d_0\cos^2\omega t\rangle = -\frac{e^2E_0(z)}{2m\omega^2}, \tag{5}$$

or, if we express the force in terms of a pseudo-potential

$$F = -e\frac{\partial V_{\rm ps}}{\partial z} \Longrightarrow V_{\rm ps} = \frac{eE_0^2(z)}{4m\omega^2}. \tag{6}$$

One can see from eqs. (5) and (6) that in an inhomogeneous RF electric field there is a net force on charged particles pulling them towards the region of lower field amplitude. This force is proportional to the square of the charge so that both positively and negatively charged particles are attracted to the lower field amplitude region. Therefore, all one needs to create confinement is a region with an electric field amplitude minimum. The most simple such structure is the quadrupole trap shown on the left side of fig. 1, the so-called Paul trap [1]. By symmetry the electric field is zero at the center and increases in amplitude in all directions. The Paul trap is a versatile confinement device that has seen much use in various fields of physics. The geometry of the Paul trap is not however most suitable to inject ion beams into, a more elongated structure is required to offer a longer path length through the device.

A more extended path length is offered by the second and third structures in fig. 1, the linear quadrupole and sextupole, which confines ions radially along their central axis. Removing energy from ions inside these structure by gas collisions will result in a centering of the ions on the symmetry axis. However, the potential inside these structures scales as r^2 or r^3, so that these devices are limited to a rather small radius by practical considerations. If larger confinement volumes are required, one must look at different structures. In particular, one cannot easily obtain a pseudo-potential that will be effective over the full volume of a larger device. Considering an extension of the quadrupole and hexapole to a very large number of poles, one can see that a small quadrant of that structure would look like a wall of rods as shown on the right of fig. 1. Such a wall, with alternating positive phase and negative phase rods, would have a very strong RF field close to the rods that diminishes rapidly as one moves away from the rods. Essentially it would form an RF wall that repels charged particles. These walls could then be molded in any form such as a box, a sphere or a cone that repels ions approaching it. A combination of such RF walls with proper DC fields could guide ions and possibly confine them over a large volume.

3 Radioactive ion beam cooling applications

The requirement for the amount of gas and the strength of the confining structure depend on the properties of the source, or mode of creation, of the radioactive ions. Three

main cases will be discussed here: cooling and bunching of poor quality ISOL type beams, cooling of fusion-evaporation reaction products, and cooling of fragmentation products. Together they give access to essentially all isotope species that have been observed to date.

3.1 Low-energy beams

Typically, ISOL type beams have energy in the 30–60 keV range with energy spread of 1–100 eV and transverse emittance of up to about $100\,\pi$ mm mrad at 60 keV. The best approach for cooling these beams is to decelerate them electrostatically to an energy of a hundred eVs or so, just above the energy spread so that all particles are still moving forward. Electrostatic deceleration is non-dissipative so that taking a typical ISOL beam with emittance of $50\,\pi$ mm mrad at 60 keV, we obtain after deceleration for a diameter of 6 mm at 100 eV a maximum divergence of roughly 400 mrad. This corresponds to a maximum transverse energy of roughly 15 eV at that point. The deceleration must therefore focus the ions into a guiding structure with a transverse guiding potential of about 20 eV depth. This is large enough to confine radially the ions while they lose their remaining energy by collisions in the gas. The stopping is best done in a light non-reactive noble gas such as helium. This yields optimum ion survival time since helium has a higher ionization potential than any other species. The amount of helium gas required to stop 100 eV heavy ions is typically about 150 mm at 0.1 mbar. The structure used for confining the ions during the final slowing down must therefore be long enough to offer a path length of 15 cm or more in the 0.1 mbar helium pressure before the ion exits the structure. Initial attempts at this task were first performed with a large RFQ trap at ISOLDE [2]. That structure offers a large enough trapping potential but the path length through the device is not sufficient for practical devices. Increasing the pressure in the device would resolve the path length issue but would also result in a reheating of the ions by gas collisions when they are reaccelerated out of the device. A more suitable structure was found to be the linear RF trap [3] (see second panel in fig. 1) which offers an elongated confining volume. The device can be used with only radial confinement in which case it just cools the beam to the gas temperature (typically room temperature) which after reacceleration yields a transverse emittance of roughly π mm mrad at 60 keV, or with an additional longitudinal confining potential which then allows one to bunch a DC beam to better match it to the experiment. Gas coolers of that type are now used in many laboratories to improve beam properties. In DC mode they reach efficiencies of roughly 30–70% when injected with ISOL type beams [4,5] at 60 or so keV and close to 100% when injected with very low energy beams [6] such as those extracted from a gas catcher (see below). The cooling times in such structure is typically tens of ms, limited by the gas pressure, and the energy spread of the extracted ions is below 1 eV. At low intensity, the transverse emittance and energy spread can be further reduced if the gas is cooled to cryogenic temperature. Used as a beam accumulator collecting beam continuously and ejecting it in a pulse mode they yield pulses of longitudinal emittance of a few eV-microseconds, ideal for injection into ion traps.

3.2 Fusion-evaporation residues

A second source of radioactive ions is fusion-evaporation reactions. Production by heavy-ion reactions on thin targets results in a radioactive recoil beam with extremely poor ion optical properties, extracted from the target by momentum conservation. The energy of the recoils depends on the kinematics of the reaction and can vary from typically 0.2 to 5 MeV/u. The momentum spread and angular divergence depend on the details of the reaction, in particular the excitation energy of the compound nucleus and the mass and energy of the evaporated particles. Momentum spread of the reaction products is typically 1–15% and angular spread can extend beyond 150 mrad. Although the recoil beam properties are very poor, the fact that the ions are extracted instantly, and that all species can be obtained, make this source still unique for beams of many species.

Slowing down such beams, say a 3 MeV/u beam of Sn isotopes, would require 4.6 mg/cm^2 of helium. It is however not necessary to lose all the ion energy in the gas. All that is required is that the ions come to rest in the gas, so most of the energy can be lost in a solid and only the final part of the range needs to be in the gas. Since energy loss is a statistical process, not all particles with a given initial energy will have exactly the same range. This variation in range is called the range straggling and for the example given above, it is about 0.2 mg/cm^2. This intrinsic range straggling is further enhanced by the momentum spread in the beam to values up to 1 mg/cm^2. To stop this beam in the gas we therefore only require an amount of gas sufficient to absorb the total range straggling.

The approach to be used here is therefore to remove most of the energy before entering the device, use the gas volume to handle the energy spread and range straggling, and finally, use the fact that the thermalized residues are ionized to guide them out selectively from the stopping volume. The transverse emittance of these beams is large enough that a transverse confining potential of hundreds of kilovolts would be required to confine the beams during the slowing down. No practical device can yield such values and the only option remaining is to lose essentially all remaining energy in the gas so that the confining/guiding potential can start affecting the ions. The required amount of gas is however too large for a linear RF structure; the radial size required is 5–10 cm and the required path length in the gas would demand too high a gas pressure and the resulting gas flow would overwhelm any existing pumping system. A larger structure that can be operated at high pressure is required. This cannot easily be achieved with the standard multipole configurations used in linear RF structures and the selected solution is instead based on a cylindrical chamber, typically 20 cm long and 10 cm in diameter, pressurized with 100–200 mbar of helium. A

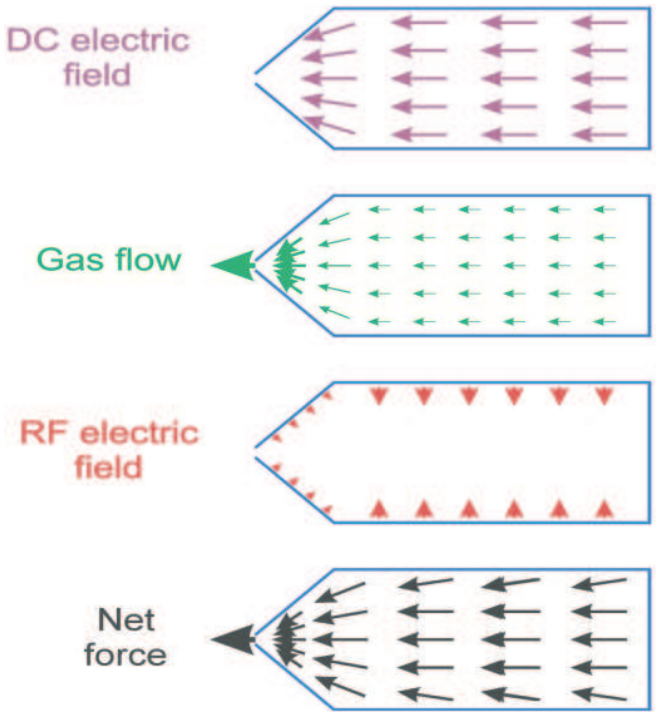

Fig. 2. Forces acting on the ions in the gas catcher. The effects of the DC electric field, gas flow, RF electric field and total forces are shown on the four catcher sketches above.

static electric field pushes the ions towards one end of the cylinder where an RF cone (based on the RF wall configuration shown in the right panel of fig. 1), consisting of a large number of plates forming a guiding structure, focuses the ions towards a nozzle where the ions are finally extracted by gas flow. The combination of the static and RF electric fields, together with the gas flow close to the nozzle, yield rapid and efficient extraction of the ions from the stopping volume (see fig. 2). Efficiencies as high as 45% and mean extraction times below 10 ms have been obtained with such a device used to inject the CPT mass spectrometer [7] at Argonne. A RF linear structure of the type mentioned in the previous section removes the ions from the gas extracted from the gas catcher and further cools the ions to yield beams with optimum properties.

3.3 Fragmentation and in-flight fission residues

A final source for short-lived isotopes is fragmentation or in-flight fission at a high-energy heavy-ion facility. This approach provides rapid extraction and separation of the isotopes of interest and access to the very neutron-rich isotope region that is not easily accessible by other techniques. The beam properties of the ions extracted from the fragmentation approach are however not suitable for many experiments and a means of cooling these beams would allow breakthrough experiments at lower energy. The gas catcher approach was proposed to fulfill this task and is now a cornerstone of the RIA project.

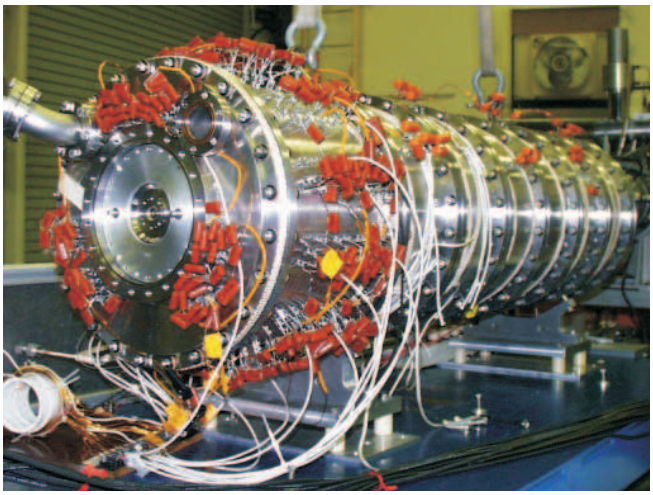

Fig. 3. Picture of the RIA gas catcher prototype built and tested at Argonne and now located at GSI for testing at the full RIA energy. The gas catcher is seen from the extraction nozzle end with the RF circuit feeding the cone structure.

Cooling fragments extracted from a fragment separator is a daunting task. The recoils have energy of 100–1000 MeV/u and a momentum spread of 1–20% depending on the production mechanism. The transverse emittance of these recoils is too high for any realistic trapping device to handle. The range and range straggling are also enormous, typically 2.2 g/cm^2 and 3 mg/cm^2 respectively for 250 MeV/u Sn recoils. The effective range straggling that one must deal with is even larger, dominated by the momentum spread of the recoils. For these same 250 MeV/u Sn recoils, the intrinsic (zero momentum spread) range straggling corresponds to 24 cm of helium gas at 500 mbar. The effect of a 0.1% momentum spread of these recoils is to increase this range straggling to 70 cm, a 1% momentum spread would require more than 5 meters of helium gas at 500 mbar.

Performing the cooling of these beams must therefore be a multistep approach. The momentum spread of the recoils must first be minimized. This is accomplished by adding a dispersive stage at the end of the fragment separator [8], followed by a wedge that removes more energy from the more energetic particles and less from the less energetic particles so that all particles exit the wedge with essentially the same energy. Much of the energy of the recoils must then be removed in an homogeneous degrader before entering the gas catcher. The helium gas volume in the gas catcher must then handle the remaining energy straggling and angular divergence of the recoils. Once the recoils are thermalized in the gas, one uses the fact that the recoils are ionized to guide them out selectively from the stopping volume. The longitudinal path length required in the gas is of the order of 2–20 mg/cm^2 while the lateral dimensions depend critically on the ion optics and achromatization stage but would typically be about 20% of the longitudinal dimension.

A device to perform this task was built at Argonne National Laboratory, essentially by scaling up the gas catcher

developed for the CPT spectrometer system. The device (see fig. 3) consists of a 1.25 meter long, 0.25 meter inner diameter, UHV chamber. Cylindrical electrodes along the body of the chamber establish a DC electric field inside the chamber to push the stopped ions towards the extraction nozzle where an RF cone made of 278 plates with alternating RF phase focuses the ions to the nozzle. The device comprises over 7400 components, with over 4000 prepared to UHV standards. It was tested at low energy with sources and with radioactive beams produced with the ATLAS accelerator [9], and reached efficiencies of up to 30% for ions stopped throughout the volume of the device. It is now at GSI where it will be tested at the full RIA energy behind the FRS fragment separator. A similar approach is being pursued at RIKEN [10].

4 Status and prospects for improvements

Cooling of radioactive ions obtained from various sources has been discussed above. The three sources mentioned have specific advantages and as such they are complementary. While the initial beam properties vary significantly between sources, it is possible to find the proper structure to cool each of these beams to essentially room temperature and obtain beam qualities comparable to those obtained with stable beams. Although these applications are fairly new, they are now present in a large number of laboratories where they are used to improve the beam properties for mass separation and better transmission through apparatus, or used to change the time structure of beams for injection in various storage devices. Efficiencies are high and the techniques are essentially universal.

A number of issues with this technology are however still present and improvements to the technology are currently trying to address many of them. The emittance of extracted beams could theoretically be even lower if the thermal bath formed by the gas was colder. Linear RF structures at cryogenic temperature are now in the commissioning phase and should soon yield beam of improved emittance for low-intensity cases. The efficiency of current ion coolers is still not optimum. Improved designs for the deceleration section leading into them, stronger radial confinement and a better sequestration and purification of the helium gas will improve the efficiency of these devices further. The delay time in these devices is still fairly large; cooling in a gas cooler takes typically 5–50 ms and the mean extraction time out of a gas catcher can vary from 5 to 200 ms depending on the size and design of the device. For gas cooler the delay time is determined by the gas pressure (and gas type) and reducing this time requires running at higher pressure. This however introduces difficulties with the extraction out of the device that can worsen the emittance obtained if performed in too high a pressure region. The creation of different pressure regions along the cooler, higher pressure in the entrance stopping region and lower pressure at the extraction end, can solve this difficulty at the cost of some additional complications. In the case of the gas catchers, larger DC guiding fields or the addition of gas circulation throughout the device can be used to speed up extraction. The final and probably most limiting aspects of the devices mention here is the limitations due to space charge. As a beam is essentially stopped for cooling, the ions spend a larger fraction of the time in a small region of space. The resulting higher concentration of charge increases the space charge repulsion they experience which can heat up the ions in the guiding/trapping structure. The problem is more severe in structures where ions are accumulated to bunch the beam. Such buncher gas cooler start observing degradation of the pulse properties at typically around 10^5 ions per bunch. Gas coolers used as continuous beam coolers can tolerate probably at least 10^8 ions per second before a similar deterioration occurs but the ion flux at which it occurs depends about the details of the device. This problem is linked to the cooling time in this case since a shorter time in the device results in a lower space charge density for a given number of ions cycling through it per seconds. Attempts are being made to quantify and model the space charge limits more carefully. The space-charge problems are further amplified in the gas catcher systems where because of the large energy loss by each incoming radioactive ions an even larger space charge is created by gas ionization. The space charge limits in these cases depend not only on the geometry but also on the energy loss of the specific radioactive ions and on the measures taken to eliminate the space charge created by the ionization. This is a key issue for many uses of this technology and a vigorous R&D program is ongoing to better determine and push back these limits.

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