Ion manipulation with cooled and bunched beams

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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.

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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.
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 $\beta$) 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