A critical review of the article by C. Rubbia, A. Ferrari, Y. Kadi, and V. Vlachoudis, *Beam cooling with ionization losses,* NIM A **568**, 475 (2006)

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Summary

What is the article about as a whole? (a) Briefly state the main topic. (b) Define the issues that the authors intend to address.

The article describes the design criteria for a new type of radioactive ion beam source. A primary beam is injected into a storage ring with a thin internal target. The purpose of the internal target is twofold: (1) to produce the desired secondary beam and (2) to provide, together with the acceleration system, a fast cooling mechanism for the primary beam (ionization cooling).

Using this principle, the primary beam is used more efficiently than in traditional techniques for secondary beam production, where most of the primary beam is lost in the target. The main technological issues of this radioactive ion beam source are the cooling of the target, the extraction scheme for the secondary beam, and longitudinal cooling. These issues are addressed in the paper and it is concluded that they are not insurmountable.

This concept of a radioactive ion beam source has several applications, such as the generation of pure neutrino beams (*beta beams*), the preparation of radioactive beams for nuclear physics, or the production of radioactive isotopes for hadron therapy.

Analysis

What is being stated in detail and how? (a) List the main parts of the paper (which usually correspond to sections and paragraphs) and summarize their content, identifying the main statements and logical arguments. (b) Identify keywords and compile a glossary with your own definitions.

The article is divided into 13 sections.

1. Introduction Layout of the apparatus: storage ring, internal target, rf cavity. High efficiency compared to traditional sources. Ionization cooling well suited for heavy ions involved in nuclear interactions. Application of the reactions $^7\mathrm{Li}+d \rightarrow^8 \mathrm{Li}+p$ and $^6\mathrm{Li}+^3\mathrm{He} \rightarrow^8 \mathrm{B}+n$ to the production of beta beams and to hadron therapy.

2. Exploiting Reverse Kinematics Collisions of a heavy ion on a light target generate reaction products in a narrow cone, so they can be more easily extracted. Choice of target material determined by the requirements of cooling and by availability. Production rate proportional to the circulating beam current and to target thickness.

3. Ionization of Heavy Ions Estimates of the average energy loss and its fluctuations. Estimates of the electron capture and ionization cross sections for the determination of equilibrium charge states. Distribution of the scattering angles due to multiple Coulomb scattering.

4. Transverse Dynamics Interplay between cooling (energy loss plus rf acceleration) and heating processes (multiple Coulomb scattering). Calculation of the cooling time and of the equilibrium emittance. The equilibrium emittance does not depend on the thickness of the internal target.

5. Longitudinal Dynamics The negative derivative of the stopping power implies a widening of the energy distribution of the circulating beam. For cooling, it is necessary, for instance, to have a variable target thickness in a dispersive region of the ring. The heating mechanism is the dispersion in energy loss.

6. Transverse and Longitudinal Cooling and Heating Introducing a longitudinal cooling mechanism reduces the horizontal cooling rate.

7. Monte Carlo Simulations of the Process A scenario for transverse and longitudinal cooling is presented, using reasonable ring parameters.

8. Achievable Performance The maximum achievable secondary beam intensity is limited by the current of the primary beam, by the energy deposition in the internal target, by the radioactivity of the source, and by space charge in the circulating beam. For the reaction $^7\mathrm{Li}+d \rightarrow^8 \mathrm{Li}+p$, it is possible to reach 10^{14} events/s. Higher intensities are reachable with a set of rings operating in parallel.

9. Target Design At peak power (~ 1 MW), it is necessary to use a gaseous target in order to dissipate the power deposited by the primary beam. One can take advantage of the results of the SGI project (*Supersonic Gas Injector*), developed for nuclear fusion. The wedge profile can be obtained using a set of independent jet targets.

10. Collection of Secondary Ions Collection and neutralization scheme based on diffusion and effusion in thin heated foils, similar to those employed by ISOLDE at CERN. Data on release times is available. Diffusion of lithium in tantalum foils is promising.

11. Practical Considerations Summary of the characteristics and parameters of the primary beam, gaseous target, storage ring, rf cavity, and collection system.

12. Conclusions Summary of the contents of the paper.

13. Comments Added in Proof Reference to the article by Y. Mori, *Development of FFAG accelerators and their applications for intense secondary particle production*, NIM A **562**, 591 (2006), which discusses a similar concept, but without addressing the issues of longitudinal cooling (which is not critical for an FFAG) and energy deposition in the target.

Keywords

beta beams	Pure and collimated neutrino beams generated by the decay of radioactive nuclei circulating in a storage ring.
Coulomb scattering	Electrostatic scattering of the ion beam on nuclei in the target, whose main effect is an increase in transverse emittance.
energy straggling	Statistical fluctuations of the beam energy loss through a target, which causes longitudinal heating.
ionization cooling	Method of beam cooling based on the interplay between an absorber and an acceleration system. As they traverse the absorber, particles lose momentum in the direction of motion. In the accelerating cavity, momentum is restored along the ideal trajectory. The combined effect is damping of transverse oscillations. To obtain longitudinal cooling, it is necessary to couple the longitudinal and transverse degrees of freedom through, for instance, a wedge absorber placed in a dispersive region of the ring.
reverse kinematics	Nuclear reaction configuration in which a heavier nucleus scatters off a lighter nucleus at rest in the laboratory frame.
rf cavity	Electromagnetic resonant cavity in the radiofrequency range (MHz to GHz), used for beam acceleration with longitudinal electric fields.
stripper foil	Thin target used to change the charge state distribution of ion beams as they traverse it.

Assessment

Are the statements and claims made in the article correct? What consequences do they have? (a) Determine whether there are any parts where the authors are uninformed (lack of information), misinformed (incorrect understanding of the information), illogical (consequences that do not follow from premises) or where the discussion is incomplete (missing important aspects). (b) Which problems have been solved? Which ones remain open? (c) Discuss possible applications or extensions.

The concept presented in the paper has a wide range of applications. For the production of neutrino beams, the performance of the apparatus needs to be pushed to the technological limits. The generation of radioactive beams for nuclear physics, on the other hand, is more easily achievable. Also interesting is the possibility of producing $\alpha + \beta^+$ emitters for hadron therapy, as they combine high dose concentrations with the ability to monitor dose deposition in real time through positron emission tomography (PET).

The writing of the paper appears rushed. There are several typos. One important error can be found in several sections: the estimate of the energy deposition in the target (1 MW) is too pessimistic; it should be 0.35 MW (the charge of the lithium ions, $Z = 3$, was counted twice).

The core idea, i.e. the combination of ionization cooling with an internal production target, should be emphasized in the title. Instead, the title focuses on ionization cooling, which is not a new concept.

A detailed analysis of achievable cooling rates and alternative scenarios was described in D. Neuffer, *Low-energy ionization cooling of ions for beta beam sources*, NIM A **585**, 109 (2008).