# Radioactive Ions Production Ring for Beta-Beams

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**Abstract**

Within the FP7 EUROnu program, Work Package 4 addresses the issues of production and acceleration of $^8$Li and $^8$B isotopes through the Beta-Beam complex, for the production of electron-neutrino. One of the major critical issues is the production of a high enougth ion flux, to fulfill the requirements for physics. In alternative to the direct ISOL production method, a new approach is proposed in [1]. The idea is to use a compact ring for Litium ions at 25 MeV and an internal He or D target, in which the radioactive-isotopes production takes place. The beam is expected to survive for several thousands of turns, therefore cooling in 6D is required and, according this scheme, the ionization cooling provided by the target itself and a suitable RF system would be sufficient. We present some preliminary work on the Production ring lattice design and cooling issues, for the $^7$Li ions, and propose plans for future studies, within the EUROnu program.

## 1 Introduction

The Beta-beam concept foresees the production of pure electron-(anti)neutrinos for oscillation experiments from the beta-decay of suitable isotopes [2]. One of its major challenges is the production of a high enough flux ($10^{14}$/s) of radioactive ions. In order to enhance the production of $^8$Li and $^8$B, studied under the FP7-EURONU Work Package 4 [3], Ref. [1] proposes the use of a compact storage ring for Lithium ions at $\sim$25 MeV and a Deuterium (or Helium) internal gas-jet target in which the nuclear reactions $^7$Li(d,p)$^8$B or $^6$Li($^3$He,n)$^8$B take place. The produced isotopes are collected by a ring-shaped Tantalum foil collection device, where a diffusion/effusion ISOLDE-like mechanism allows the extraction of the $^8$Li or $^8$B to an ECR source. The circulating beam is stored for several thousands of turns and cooling both in the transverse and in the longitudinal plane is required to compensate for Multiple Coulomb scattering and energy straggling at the target.

Storage rings with internal targets [4] are usually equipped with electron and or stochastic coolers, but according to the scheme proposed in Ref. [1], the ionization cooling provided by the target and a suitable RF system would be sufficient. A similar concept was applied in the design of ERIT, a proton FFAG with an internal Beryllium target for the production of neutrons [5] which was built in KURRI, Japan, but in this case longitudinal cooling was not needed because of the large FFAG acceptance.

Ionization cooling [6] is recently receiving large attentions for the fast cooling of muons for a Neutrino Factory or a Muon Collider [7]. It is based on the principle that a beam traversing a material (absorber) looses energy and only its longitudinal component is recovered in the RF cavities, with the net effect of a transverse emittance shrinking. Longitudinal ionization cooling can be achieved at expenses of the horizontal one, by introducing coupling between the two planes, via the dispersion, and by using a wedge-shaped absorber in a high dispersive region. In analogy to radiation damping one can introduce partition numbers, whose sum is invariant, to characterize the cooling rates in the three planes and define equilibrium emittances from the balance between the cooling term and the heating one, the latest induced by Multiple Coulomb scattering or energy straggling [7].

The challenge of applying ionization cooling for low-energy ions resides in the strongly negative slope of the Bethe-Bloch formula [8] for the energies of interest. In particular, $(\partial E_{loss}/\partial p)<0$ means that for an increase of particle momentum, the energy losses in the material becomes weaker, thus causing

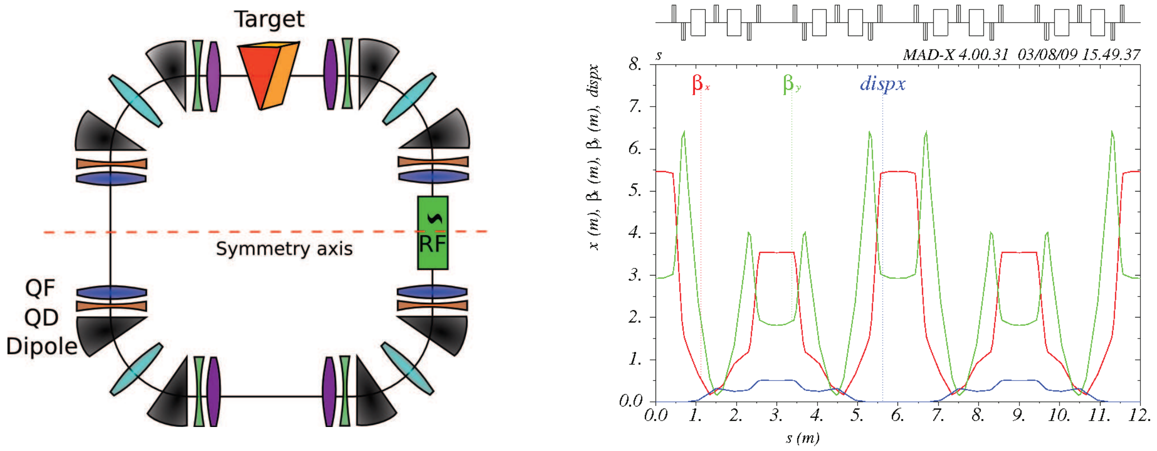

**Fig. 1:** Production ring sketch (left) and Twiss parameters (right).

heating instead of cooling in the longitudinal plane. This can be overcome by introducing coupling via the dispersion, but the sums of the partition numbers is in this case only slightly positive [9].

## 2 The proposed lattice

The development of a 12m-long production-ring lattice for the 25 MeV $^7$Li ions (magnetic rigidity, $B\rho \sim 0.6$) is well documented in Ref. [10]. The layout, based on double-bend achromatic cells, includes five quadrupole families to allow for a high flexibility and has a two-fold symmetry, as shown in Fig. 1. Two of the straight sections have zero dispersion, in order to accommodate the RF cavity(ies). The other two straight sections, instead, are characterized by a relatively high value of horizontal dispersion ($D_x$ ∼50 cm), as required by the specifications for the production target, which will be installed in one of them. For the magnets, the normal-conducting technology has been chosen and the study includes a first evaluation of the required aperture, assuming an rms emittance of ∼10 mm mrad. The maximum beta is about $\beta_{max}$ ∼5 m and the tunes are $Q_x = 2.56$ and $Q_y = 1.59$, but can be easily changed.

## 3 Monte-carlo simulations

The interactions between the beam and the target were simulated with Geant4 [11] and the supersonic Deuterium gas-jet target was modeled [12] as a solid block of material with a thickness of about $t$=300 $\mu$g/cm$^2$ ($9 \times 10^{19}$ atoms/cm$^2$) to give a mean energy loss of ∼300 keV per passage, as from Ref. [1]. The hadronic model implemented in Geant4 was shown not to be adequate at the (low) energies of interest, while for the electro-magnetic interactions there is a good agreement with the Bethe-Bloch formula and the following Multiple Coulomb Scattering angle formula:

$$\theta_c = \frac{14.1MeV}{\beta cp} z \sqrt{\frac{t}{\chi_0}} \left[1 + 0.038 \ln \frac{t}{\chi_0}\right] \tag{1}$$

Geant4 simulations allowed the determination of the minimum value of dispersion to achieve cooling in the longitudinal plane as a function of the target wedge angle. In particular, if we assume an angle of 20$^o$, the dispersion at the target should be $D_x > 0.24$ m. In the designed lattice it is $D_x \sim 0.5$ m.

Preliminary 6D-tracking simulations were done [12] by implementing the beam transport matrices and the RF-cavity kick in C++ classes and by coupling them to the Geant4 tracking inside the target. Figure 2 proves that changing the target wedge angle allows to transfer the cooling from the horizontal plane to the longitudinal and vice versa.

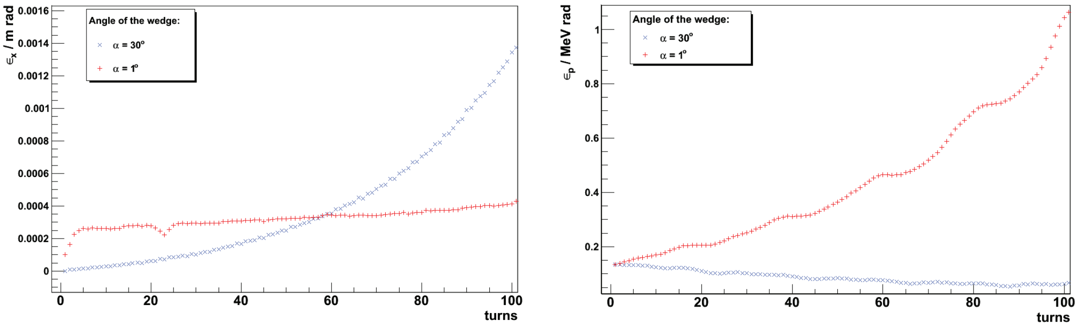

**Fig. 2:** Horizontal (left) and longitudinal (right) emittance evolution for two different wedge angles

## 4 Conclusions and ongoing work

The production ring looks a promising alternative for achieving a high flux of radioactive isotopes for a Beta-beam Facility. A preliminary lattice has been set-up and Monte-carlo simulations show that one can transfer cooling from the horizontal to the longitudinal plane by having a wedge-shaped target in a dispersive region. Future work includes more studies on the side of the production cross-sections and on the range of validity of the electromagnetic-interaction models. Tracking simulations with the code SixTrack [13], already started in Ref. [10], will be continued and compared to the Geant4 and C++ classes results. They will lead to lattice optimization and a to get a better feeling on the effects of coupling on the cooling rates. In addition to that, technological issues e.g. the collection efficiency of the produced isotopes and the supersonic gas-jet target characteristics will have to be addressed and other possible show-stoppers or production-limiting factors identified and analized.

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